U.S. Department of Energy Hydrogen and Fuel Cells Program:

2018 Annual Merit Review and Peer Evaluation Report

June 13–15, 2018
Washington, DC

U.S. DEPARTMENT OF
ENERGY

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NOTICE

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Prologue

Dear Colleague:

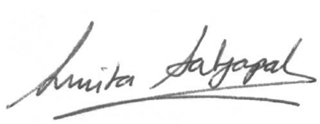
This document summarizes peer review comments and scores for the fiscal year (FY) 2018 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting (AMR), held June 13–15, 2018, in Washington, DC. In response to direction from various stakeholders, including the National Academies, this review process provides project- and program-level evaluations of DOE-funded early-stage research, development, and analysis of hydrogen and fuel cell technologies.

This year's AMR featured a number of new sessions and events, including a dedicated three-day track on the DOE Office of Fossil Energy's Solid Oxide Fuel Cell Program, a one-day session on interagency and state-level activities, and a fuel cell car ride-and-learn. The AMR kicked off with an opening plenary panel discussion with members of the Hydrogen Council, a global industry partnership of more than 40 companies committing to hydrogen infrastructure. The plenary session also featured keynote remarks by Daniel Simmons, Principal Deputy Assistant Secretary from the Office of Energy Efficiency and Renewable Energy (EERE), and program and sub-program overview presentations. The AMR was attended by more than 800 participants, including 176 reviewers who reviewed 116 projects.

DOE values the transparent public process of soliciting technical input on its projects and overall programs from relevant experts with depth and breadth of knowledge across a number of broad areas. The reviewers' recommendations are taken into consideration by DOE technology managers in generating future work plans. The table in this report lists the projects presented at the review and the overall evaluation score for each project. The individual reports present the reviewer comments to be considered during the upcoming fiscal year (October 1, 2018–September 30, 2019). The projects have been grouped according to sub-program and reviewed according to the appropriate evaluation criteria. To furnish principal investigators (PIs) with direct feedback, all of the evaluations and comments are provided to each presenter; however, the authors of the individual comments remain anonymous. DOE instructs the PIs to fully consider these summary evaluation comments, along with any other comments by DOE managers, in their FY 2019 plans. In addition, DOE managers contact each PI individually and discuss the comments and recommendations as future plans are developed.

In addition to thanking all participants in the AMR, I would like to express my sincere appreciation to the reviewers for your strong commitment, expertise, and dedication in advancing hydrogen and fuel cell technologies. You make this report possible, and we rely on your comments, along with other management processes, to help make project decisions for the new fiscal year. We look forward to your participation in the FY 2019 AMR, which is scheduled for April 29–May 1, 2019, in Washington, DC. Thank you for participating in the FY 2018 AMR.

Sincerely,



Sunita Satyapal
Director
Hydrogen and Fuel Cells Program
U.S. Department of Energy

Hydrogen Fuel R&D

Hydrogen Production and Delivery R&D

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
PD-025	Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service *Joe Ronevich; Sandia National Laboratories*	3.4			X
PD-100	700 bar Hydrogen Dispenser Hose Reliability Improvement *Kevin Harrison; National Renewable Energy Laboratory*	3.5	X		
PD-108	Hydrogen Compression Application of the Linear Motor Reciprocating Compressor *Eugene Broerman; Southwest Research Institute*	2.8	X		
PD-131	Magnetocaloric Hydrogen Liquefaction *Jamie Holladay; Pacific Northwest National Laboratory*	3.1	X		
PD-135	Liquid Hydrogen Infrastructure Analysis *Guillaume Petitpas; Lawrence Livermore National Laboratory*	3.4			X
PD-136	Electrochemical Compression *Monjid Hamdan; Giner ELX, Inc.*	3.5	X		
PD-137	Hybrid Electrochemical–Metal Hydride Compression *Scott Greenway; Greenway Energy, Inc.*	3.1	X		
PD-138	Metal Hydride Compression *Terry Johnson; Sandia National Laboratories*	3.6	X		
PD-140	Dispenser Reliability *Michael Peters; National Renewable Energy Laboratory*	3.2	X		
PD-143	High-Temperature Alkaline Water Electrolysis *Hui Xu; Giner, Inc.*	3.4	X		
PD-146	Advancing Hydrogen Dispenser Technology by Using Innovative Intelligent Networks *Darryl Pollica; Ivys Inc.*	3.4	X		
PD-149	Hydrogen Dispensing Hose *Jennifer Lalli; NanoSonic, Inc.*	3.2	X		
PD-150	Coatings for Compressor Seals *Shannan O'Shaughnessy; GVD Corporation*	3.3	X		
PD-151	New Approaches to Improved Polymer Electrolyte Membrane Electrolyzer Ion-Exchange Membranes *Earl Wagener; Tetramer Technologies, LLC*	3.1	X		

Hydrogen Production and Delivery R&D: HydroGEN Seedling

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
PD-148	HydroGEN Overview: A Consortium on Advanced Water-Splitting Materials *Huyen Dinh; National Renewable Energy Laboratory*	3.6	X*		
PD-152	Proton-Conducting Solid Oxide Electrolysis Cells for Large-Scale Hydrogen Production at Intermediate Temperatures *Prabhakar Singh; University of Connecticut*	3.3	X*		
PD-153	Degradation Characterization and Modeling of a New Solid Oxide Electrolysis Cell Utilizing Accelerated Life Testing *Scott Barnett; Northwestern University*	3.4	X*		
PD-154	Thin-Film, Metal-Supported High-Performance and Durable Proton–Solid Oxide Electrolyzer Cell *Tianli Zhu; United Technologies Research Center*	3.2	X*		
PD-155	High-Efficiency Polymer Electrolyte Membrane Water Electrolysis Enabled by Advanced Catalysts, Membranes, and Processes *Kathy Ayers; Proton OnSite*	3.3	X*		
PD-156	Developing Novel Platinum-Group-Metal-Free Catalysts for Alkaline Hydrogen and Oxygen Evolution Reactions *Sanjeev Mukerjee; Northeastern University*	3.3	X*		
PD-157	Platinum-Group-Metal-Free Oxygen Evolution Reaction Catalysts for Polymer Electrolyte Membrane Electrolyzer *Di-Jia Liu; Argonne National Laboratory*	3.5	X*		
PD-158	High-Performance Ultralow-Cost Non-Precious-Metal Catalyst System for Anion-Exchange Membrane Electrolyzer *Hoon Chung; Los Alamos National Laboratory*	3.2	X*		
PD-159	Scalable Elastomeric Membranes for Alkaline Water Electrolysis *Yu Seung Kim; Los Alamos National Laboratory*	3.4	X*		
PD-160	Best-in-Class Platinum-Group-Metal-Free Catalyst Integrated Tandem Junction Photoelectrochemical Water-Splitting Devices *Charles Dismukes; Rutgers University*	3.6	X*		
PD-161	Protective Catalyst Systems on III-V and Silicon-Based Semiconductors for Efficient, Durable Photoelectrochemical Water-Splitting Devices *Thomas Jaramillo; Stanford University*	3.7	X*		

* HydroGEN seedling projects marked "Continue" are on track, but project continuation is contingent on passing a go/no-go decision.

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
PD-162	Novel Chalcopyrites For Advanced Photoelectrochemical Water Splitting *Nicolas Gaillard; University of Hawaii*	3.6	X*		
PD-163	Monolithically Integrated Thin-Film/Silicon Tandem Photoelectrodes for High-Efficiency and Stable Photoelectrochemical Water Splitting *Zetian Mi; University of Michigan*	3.3	X*		
PD-164	Efficient Solar Water Splitting with 5,000-Hour Stability Using Earth-Abundant Catalysts and Durable Layered Two-Dimensional Perovskites *Aditya Mohite; Los Alamos National Laboratory*	3.7	X*		
PD-165	Accelerated Discovery of Solar Thermochemical Hydrogen Production Materials via High-Throughput Computational and Experimental Methods *Ryan O'Hayre; Colorado School of Mines*	3.3	X*		
PD-166	Computationally Accelerated Discovery and Experimental Demonstration of High-Performance Materials for Advanced Solar Thermochemical Hydrogen Production *Charles Musgrave; University of Colorado Boulder*	3.6	X*		
PD-167	Transformative Materials for High-Efficiency Thermochemical Production of Solar Fuels *Chris Wolverton; Northwestern University*	2.9	X*		
PD-168	Mixed Ionic Electronic Conducting Quaternary Perovskites: Materials by Design for Solar Thermochemical Hydrogen *Ellen Stechel; Arizona State University*	3.4	X*		
PD-169	High-Temperature Reactor Catalyst Material Development for Low-Cost and Efficient Solar-Driven Sulfur-Based Processes *Claudio Corgnale; Greenway Energy*	3.2	X*		

* HydroGEN seedling projects marked "Continue" are on track, but project continuation is contingent on passing a go/no-go decision.

Hydrogen Storage R&D

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
ST-001	System-Level Analysis of Hydrogen Storage Options *Rajesh Ahluwalia; Argonne National Laboratory*	3.4	X		
ST-008	Hydrogen Storage System Modeling: Public Access, Maintenance, and Enhancements *Matt Thornton; National Renewable Energy Laboratory*	3.4	X		
ST-100	Hydrogen Storage Cost Analysis *Brian James; Strategic Analysis, Inc.*	3.1	X		
ST-122	Hydrogen Adsorbents with High Volumetric Density: New Materials and System Projections *Don Siegel; University of Michigan*	3.3			X
ST-127	Hydrogen Materials—Advanced Research Consortium (HyMARC): A Consortium for Advancing Hydrogen Storage Materials *Mark Allendorf; Sandia National Laboratories*	3.5	X		
ST-128	Hydrogen Materials—Advanced Research Consortium (HyMARC): Sandia National Laboratories Technical Activities *Mark Allendorf; Sandia National Laboratories*	3.5	X		
ST-129	Hydrogen Materials—Advanced Research Consortium (HyMARC): Lawrence Livermore National Laboratory Technical Activities *Brandon Wood; Lawrence Livermore National Laboratory*	3.6	X		
ST-130	Hydrogen Materials—Advanced Research Consortium (HyMARC): Lawrence Berkeley National Laboratory Technical Activities *Jeffrey Urban; Lawrence Berkeley National Laboratory*	3.3	X		
ST-131	Hydrogen Materials—Advanced Research Consortium (HyMARC): National Renewable Energy Laboratory Technical Activities *Thomas Gennett; National Renewable Energy Laboratory*	3.5	X		
ST-132	Hydrogen Materials—Advanced Research Consortium (HyMARC): Pacific Northwest National Laboratory Technical Activities *Tom Autrey; Pacific Northwest National Laboratory*	3.5	X		
ST-133	Hydrogen Materials—Advanced Research Consortium (HyMARC): Lawrence Berkeley National Laboratory Technical Activities *Jeffrey Long; Lawrence Berkeley National Laboratory*	3.4	X		

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
ST-138	Hydrogen Materials—Advanced Research Consortium (HyMARC) Seedling: Development of Magnesium Boride Etherates as Hydrogen Storage Materials *Godwin Severa; University of Hawaii*	3.5	X		

Fuel Cell R&D

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
FC-017	Fuel Cell System Modeling and Analysis *Rajesh Ahluwalia; Argonne National Laboratory*	3.4	X		
FC-117	Fiscal Year 2015 Small Business Innovation Research (Phase II Release 2): Ionomer Dispersion Impact on Polymer Electrolyte Membrane Fuel Cell and Electrolyzer Durability *Hui Xu; Giner, Inc.*	3.0	X		
FC-128	Facilitated Direct Liquid Fuel Cells with High-Temperature Membrane Electrode Assemblies *Emory DeCastro; Advent Technologies, Inc.*	3.0	X		
FC-135	Fuel Cell Consortium for Performance and Durability *Rod Borup; Los Alamos National Laboratory*	3.4	X		
FC-140	Tailored High-Performance Low-Platinum-Group-Metal Alloy Cathode Catalysts *Vojislav Stamenkovic; Argonne National Laboratory*	3.4	X		
FC-141	Platinum Monolayer Electrocatalysts *Jia Wang; Brookhaven National Laboratory*	3.4	X		
FC-142	Extended Surface Electrocatalyst Development *Bryan Pivovar; National Renewable Energy Laboratory*	3.1	X		
FC-143	Highly Active, Durable, and Ultralow-Platinum-Group-Metal Nanostructured Thin-Film Oxygen Reduction Reaction Catalysts and Supports *Andrew Steinbach; 3M*	3.1	X		
FC-144	Highly Accessible Catalysts for Durable High-Power Performance *Anusorn Kongkanand; General Motors*	3.5	X		
FC-145	Corrosion-Resistant Non-Carbon Electrocatalyst Supports for Proton Exchange Fuel Cells *Vijay Ramani; Washington University*	3.0	X		
FC-146	Advanced Materials for Fully Integrated Membrane Electrode Assemblies in Anion-Exchange Membrane Fuel Cells *Yu Seung Kim; Los Alamos National Laboratory*	3.3	X		
FC-147	Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells *Bryan Pivovar; National Renewable Energy Laboratory*	3.2	X		
FC-154	Fiscal Year 2016 Small Business Innovation Research (Phase II Release 1): Regenerative Fuel Cell System *Paul Matter; pH Matter LLC*	2.9			X

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
FC-155	Novel Ionomers and Electrode Structures for Improved Polymer Electrolyte Membrane Fuel Cell Electrode Performance at Low-Platinum-Group-Metal Loadings *Andrew Haug; 3M*	3.2	X		
FC-156	Durable High-Power Membrane Electrode Assemblies with Low Platinum Loading *Swami Kumaraguru; General Motors*	3.2	X		
FC-157	High-Performance Polymer Electrolyte Fuel Cell Electrode Structures *Mike Perry; United Technologies Research Center*	2.9		X	
FC-158	Fuel Cell Membrane Electrode Assemblies with Ultralow-Platinum Nanofiber Electrodes *Peter Pintauro; Vanderbilt University*	3.3	X		
FC-160	ElectroCat (Electrocatalysis Consortium) *Deborah Myers (Argonne National Laboratory) and Piotr Zelenay (Los Alamos National Laboratory); Los Alamos National Laboratory*	3.2	X		
FC-161	Advanced Electrocatalysts through Crystallographic Enhancement *Jacob Spendelow; Los Alamos National Laboratory*	3.2	X		
FC-162	Vapor Deposition Process for Engineering of Dispersed Polymer Electrolyte Membrane Fuel Cell Oxygen Reduction Reaction $Pt/NbO_x/C$ Catalysts *Jim Waldecker; Ford Motor Company*	3.2	X		
FC-163	Fuel Cell Systems Analysis *Brian James; Strategic Analysis, Inc.*	3.4	X		
FC-170	ElectroCat: Durable Manganese-Based Platinum-Group-Metal-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells *Hui Xu; Giner, Inc.*	3.0	X		
FC-171	ElectroCat: Advanced Platinum-Group-Metal-Free Cathode Engineering for High Power Density and Durability *Shawn Litster; Carnegie Mellon University*	3.3	X		
FC-172	ElectroCat: Highly Active and Durable Platinum-Group-Metal-Free Oxygen Reduction Reaction Electrocatalysts through the Synergy of Active Sites *Yuyan Shao; Pacific Northwest National Laboratory*	2.9		X	
FC-173	ElectroCat: Platinum-Group-Metal-Free Engineered Framework Nanostructure Catalysts *Prabhu Ganesan; Greenway Energy, LLC*	2.9		X	

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
FC-174	Highly Efficient and Durable Cathode Catalyst with Ultralow Platinum Loading through Synergetic Platinum/ Platinum-Group-Metal-Free Catalytic Interaction *Di-Jia Liu; Argonne National Laboratory*	3.3	X		
FC-175	Polymer-Based Fuel Cells That Operate from 80°C–220°C *Yu Seung Kim; Los Alamos National Laboratory*	3.1	X		
FC-176	Fiscal Year 2017 Small Business Innovation Research (Phase II Release 1): Novel Hydrocarbon Ionomers for Durable Polymer Electrolyte Membranes *William Harrison; Nanosonic, Inc.*	2.8		X	

Technology Acceleration and Hydrogen Infrastructure R&D

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
MN-001	Fuel Cell Membrane Electrode Assembly Manufacturing Research and Development *Michael Ulsh; National Renewable Energy Laboratory*	3.4	X		
MN-015	Continuous Fiber Composite Electrofusion Coupler *Brett Kimball; Automated Dynamics*	2.6	X		
MN-016	In-Line Quality Control of Polymer Electrolyte Membrane Materials *Paul Yelvington; Mainstream*	3.2	X		
MN-017	Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations *Margaret Mann; National Renewable Energy Laboratory*	3.1			X
MN-018	Roll-to-Roll Advanced Materials Manufacturing Lab Consortium *Claus Daniel; Oak Ridge National Laboratory*	3.2	X		
MT-008	Hydrogen Energy Systems as a Grid Management Tool *Mitch Ewan; Hawaii Natural Energy Institute*	3.3		X	
MT-011	Fuel-Cell-Powered Airport Ground Support Equipment Deployment *Larry Pitts; Plug Power*	3.3	X		
MT-013	Maritime Fuel Cell Generator Project *Lennie Klebanoff; Sandia National Laboratories*	3.3	X		
MT-014	Demonstration of Fuel Cell Auxiliary Power Unit to Power Truck Refrigeration Units in Refrigerated Trucks *Kriston Brooks; Pacific Northwest National Laboratory*	3.1			X
MT-017	FedEx Express Hydrogen Fuel Cell Extended-Range Battery Electric Vehicles *Phillip Galbach; FedEx Express*	3.2	X		
MT-021	Northeast Demonstration and Deployment of FCRx200 *Abas Goodarzi; US Hybrid*	3.0	X		
TV-001	Fuel Cell Electric Vehicle Evaluation *Jennifer Kurtz; National Renewable Energy Laboratory*	3.5	X		
TV-008	Fuel Cell Bus Evaluations *Leslie Eudy; National Renewable Energy Laboratory*	3.9	X		
TV-017	Hydrogen Station Data Collection and Analysis *Sam Sprik; National Renewable Energy Laboratory*	3.4	X		
TV-029	Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High-Pressure Liquid Hydrogen Pump *Salvador Aceves; Lawrence Livermore National Laboratory*	2.9			X

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
TV-031	Dynamic Modeling and Validation of Electrolyzers in Real-Time Grid Simulation *Rob Hovsapian; Idaho National Laboratory*	3.7	X		
TV-034	Fuel Cell Hybrid Electric Delivery Van *Jason Hanlin; Center for Transportation and the Environment*	3.2	X		
TV-039	Innovative Advanced Hydrogen Mobile Fueler *Sara Odom; Electricore*	3.5		X	
TV-040	High-Temperature Electrolysis Test Stand *Richard Boardman; Idaho National Laboratory*	3.7	X		
TV-041	Modular Solid Oxide Electrolyzer Cell System for Efficient Hydrogen Production at High Current Density *Hossein Ghezel-Ayagh; FuelCell Energy*	3.5	X		
TV-042	Optimal Stationary Fuel Cell Integration and Control (Energy Dispatch Controller) *Genevieve Saur; National Renewable Energy Laboratory*	3.3	X		
TV-043	Integrated Systems Modeling of the Interactions between Stationary Hydrogen, Vehicle, and Grid Resources *Samveg Saxena; Lawrence Berkeley National Laboratory*	3.2	X		
TV-045	H2@Scale Analysis *Mark Ruth; National Renewable Energy Laboratory*	3.6	X		
TV-146	H2@Scale: Experimental Characterization of Durability of Advanced Electrolyzer Concepts in Dynamic Loading *Shaun Alia; National Renewable Energy Laboratory*	3.7	X		
TV-148	Hydrogen Stations for Urban Sites *Brian Ehrhart; National Renewable Energy Laboratory/ Sandia National Laboratories*	3.2	X		
TV-149	Mirai Testing *Henning Lohse-Busch; Argonne National Laboratory*	3.7			X
TV-150	Analysis of Fuel Cells for Trucks *Ram Vijayagopal; Argonne National Laboratory*	3.2	X		

Safety, Codes and Standards

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SCS-001	National Codes and Standards Deployment and Outreach *Carl Rivkin; National Renewable Energy Laboratory*	3.6	X		
SCS-005	Research and Development for Safety, Codes and Standards: Materials and Component Compatibility *Chris San Marchi; Sandia National Laboratories*	3.8	X		
SCS-007	Fuel Quality Assurance Research and Development and Impurity Testing in Support of Codes and Standards *Tommy Rockward; Los Alamos National Laboratory*	3.4	X		
SCS-010	Research and Development for Safety, Codes and Standards: Hydrogen Behavior *Ethan Hecht; Sandia National Laboratories*	3.5	X		
SCS-011	Hydrogen Quantitative Risk Assessment *Alice Muna; Sandia National Laboratories*	3.4	X		
SCS-019	Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources *Nick Barilo; Pacific Northwest National Laboratory*	3.7	X		
SCS-021	National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory *William Buttner; National Renewable Energy Laboratory*	3.4	X		
SCS-025	Enabling Hydrogen Infrastructure through Science-Based Codes and Standards *Chris LaFleur; Sandia National Laboratories*	3.6	X		
SCS-026	Compatibility of Polymeric Materials Used in the Hydrogen Infrastructure *Kevin Simmons; Pacific Northwest National Laboratory*	3.5			X
SCS-030	Advancing Fuel Cell Electric Vehicles in San Francisco and Beyond *Jessie Denver; City and County of San Francisco*	3.0	X		

Systems Analysis

Project Number	Project Title *Principal Investigator Name & Organization*	Final Score	Continue	Discontinue/ Further Review	Completed
SA-039	Regional Water Stress Analysis with Hydrogen Production at Scale *Amgad Elgowainy; Argonne National Laboratory*	3.4		X	
SA-044	Cost–Benefit Analysis of Technology Improvement in Light-Duty Fuel Cell Vehicles *Aymeric Rousseau; Argonne National Laboratory*	3.5	X		
SA-059	Sustainability Analysis: Hydrogen Regional Sustainability *Elizabeth Connelly; National Renewable Energy Laboratory*	3.2			X
SA-063	Regional Supply of Hydrogen *Michael Penev; National Renewable Energy Laboratory*	3.3	X		
SA-169	Market Segmentation Analysis of Medium- and Heavy-Duty Trucks with a Fuel Cell Emphasis *Chad Hunter; National Renewable Energy Laboratory*	3.0	X		
SA-170	Analysis of Cost Impacts of Integrating Advanced Onboard Storage Systems with Hydrogen Delivery *Amgad Elgowainy; Argonne National Laboratory*	3.2	X		

Table of Contents

Introduction

The fiscal year (FY) 2018 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program) Annual Merit Review and Peer Evaluation Meeting (AMR) was held June 13–15, 2018, at the Washington Marriott Wardman Park Hotel in Washington, DC. This report is a summary of comments by AMR peer reviewers about the hydrogen and fuel cell projects funded by DOE's Office of Energy Efficiency and Renewable Energy (EERE). Projects supported by other state agencies and DOE offices (including the Office of Fossil Energy Solid Oxide Fuel Cell Program [FE-SOFC)], Office of Science [Basic Energy Sciences], Advanced Research Projects Agency – Energy [ARPA-E], and EERE Advanced Manufacturing Office) in areas relevant to hydrogen and fuel cells were also presented at the FY 2018 AMR. DOE uses the results of this merit review and peer evaluation, along with additional review processes, to make funding decisions for upcoming fiscal years and help guide ongoing performance improvements to existing projects.

The objectives of this meeting include the following:

- Review and evaluate FY 2018 accomplishments and FY 2019 plans for DOE laboratory programs; industry/university cooperative agreements; and related research, development, and demonstration (RD&D) efforts.
- Provide an opportunity for stakeholders and participants (e.g., fuel cell and hydrogen system manufacturers, component developers, and others) to provide input to help shape the DOE-sponsored RD&D program in order to address the highest-priority technical barriers and facilitate technology transfer.
- Foster interactions among the national laboratories, industry, and universities conducting RD&D.

The peer review process followed the guidelines in the *Peer Review Guide* developed by EERE. The peer review panel members, listed in Table 1, provided comments about the projects presented. Panel members included experts from a variety of backgrounds related to hydrogen and fuel cells, and they represented national laboratories; universities; various government agencies; and manufacturers of hydrogen production, storage, delivery, and fuel cell technologies. Each reviewer was screened for conflicts of interest as prescribed by the *Peer Review Guide*. A subset of these reviewers was also asked to provide overall Program and sub-program review feedback. The results of this Program Review feedback are included in Appendix A. A complete list of the meeting participants is presented in Appendix B.

Table 1: Peer Review Panel Members

No.	Name	Organization
1	Kareem Afzal	PDC Machines, Inc.
2	Antonio Aguilo-Rullan	Fuel Cells And Hydrogen Joint Undertaking (FCH JU)
3	Rajesh Ahluwalia	Argonne National Laboratory
4	Paul Albertus	Advanced Research Projects Agency–Energy (ARPA-E)
5	Shaun Alia	National Renewable Energy Laboratory
6	Laurent Antoni	Commissariat à l'énergie atomique et aux énergies alternatives (CEA, French Atomic Energy Commission)
7	Katherine Ayers	Proton OnSite
8	Dustin Banham	Ballard Power Systems
9	Nick Barilo	Pacific Northwest National Laboratory
10	Jean Baronas	California Energy Commission
11	Olga Baturina	U.S. Naval Research Laboratory
12	Guido Bender	National Renewable Energy Laboratory
13	Matthew Bliekse	Shell Global New Energies
14	Richard Boardman	Idaho National Laboratory
15	Rodney Borup	Los Alamos National Laboratory
16	Nico Bouwkamp	California Fuel Cell Partnership/Frontier Energy
17	Peter Bouwman	Nedstack
18	Antonio Bouza	U.S. Department of Energy
19	Robert Bowman	Oak Ridge National Laboratory (retired)
20	Kenneth Boyce	UL

No.	Name	Organization
21	Jack Brouwer	University of California, Irvine
22	Susan Burke	U.S. Environmental Protection Agency
23	James Burns	University of Virginia
24	Scott Calabrese Barton	Michigan State University
25	Pietro Caloprisco	Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
26	Kevin Centeck	U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)
27	Bryan Chapman	ExxonMobil
28	Santanu Chaudhuri	Argonne National Laboratory
29	Praveen Cheekatamarla	Atrex Energy, Inc.
30	Dejun Chen	Georgetown University
31	Biswajit Choudhury	E. I. du Pont de Nemours and Company (DuPont)
32	Eric Coker	Sandia National Laboratories
33	William Collins	WPCSOL, LLC (consultant)
34	Hector Colon-Mercado	Savannah River National Laboratory
35	David Cullen	Oak Ridge National Laboratory
36	Nilesh Dale	Nissan Technical Center North America, Inc.
37	Nemanja Danilovic	Lawrence Berkeley National Laboratory
38	Daniel DeSantis	Strategic Analysis, Inc.
39	Todd Deutsch	National Renewable Energy Laboratory
40	Huyen Dinh	National Renewable Energy Laboratory
41	Tabbetha Dobbins	Rowan University
42	Martin Dornheim	Helmholtz–Zentrum Geesthacht Centre for Materials and Coastal Research
43	Tyson Eckerle	California Governor's Office of Business and Economic Development
44	David Edwards	Air Liquide
45	Glenn Eisman	Eisman Technology Consultants, LLC
46	S. Elongo Elangovan	OxEon Energy, LLC
47	Leslie Eudy	National Renewable Energy Laboratory
48	Mitch Ewan	University of Hawaii, Manoa/Hawaii Natural Energy Institute
49	Gary Flood	GSF Consulting, LLC
50	Prabhu Ganesan	Greenway Energy, LLC
51	Monterey Gardiner	BMW Group
52	Dominic Francis (Don) Gervasio	University of Arizona
53	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
54	William Gibbons	University of Maryland
55	Craig Gittleman	General Motors
56	Colin Gore	RedOx Power Systems
57	Leo Grassilli	U.S. Department of the Navy, Office of Naval Research (retired)
58	Markus Gross	BMW Group
59	Tom Gross	Energy Planning and Solutions
60	Stephen Grot	Ion Power
61	Katrina Groth	University of Maryland
62	Jennifer Hamilton	Frontier Energy/California Fuel Cell Partnership
63	Aaron Harris	Air Liquide
64	Kevin Harrison	National Renewable Energy Laboratory
65	Jason Hattrick-Simpers	National Institute of Standards and Technology
66	Andrew Haug	3M
67	James Hinkley	Commonwealth Scientific and Industrial Research

No.	Name	Organization
		Organization (CSIRO)
68	Shinichi Hirano	Ford Motor Company
69	Jamie Holladay	Pacific Northwest National Laboratory
70	Nick Irvin	Southern Company
71	Levi Irwin	ManTech International Corporation/U.S. Department of Energy, Solar Energy Technologies Office
72	Ian Jakupca	NASA
73	Brian James	Strategic Analysis, Inc.
74	Lisa Jerram	American Public Transportation Association
75	Nicholas Josefik	U.S. Army Corps of Engineers
76	Richard Kallman	City of Santa Fe Springs, Department of Fire – Rescue
77	Tim Karlsson	International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)
78	Joerg Karstedt	Zentrum für BrennstoffzellenTechnik (ZBT) GmbH
79	Douglass Kauffman	National Energy Technology Laboratory
80	Jay Keller	Zero Carbon Energy Solutions (consultant)
81	Ronald Kent	Southern California Gas Company/Sempra Energy
82	Yu Seung Kim	Los Alamos National Laboratory
83	Benjamin Klahr	CNA Corporation
84	Shanna Knights	Ballard Power Systems
85	Brian Koeppel	Pacific Northwest National Laboratory
86	Anusorn Kongkanand	General Motors
87	Michael Koonce	Luxfer-GTM Technologies, LLC
88	John Kopasz	Argonne National Laboratory
89	Theodore Krause	Argonne National Laboratory
90	Ahmet Kusoglu	Lawrence Berkeley National Laboratory
91	Stephan Lany	National Renewable Energy Laboratory
92	Mark Lausten	Allegheny Science & Technology, supporting U.S. Department of Energy, Solar Energy Technologies Office
93	Mark Leavitt	General Motors
94	Ludwig Lipp	T2M Global
95	Di-Jia Liu	Argonne National Laboratory
96	Meilin Liu	Georgia Institute of Technology
97	Daryl Ludlow	Ludlow Electrochemical Hardware Corporation
98	Miguel Maes	NASA White Sands Test Facility
99	Zq Mao	Tsinghua University
100	Radenka Maric	University of Connecticut
101	Andrew Martinez	California Air Resources Board
102	Sara Marxen	CSA Group
103	David Masten	General Motors
104	Christopher Matranga	National Energy Technology Laboratory
105	Paul Matter	pH Matter, LLC
106	Anthony McDaniel	Sandia National Laboratories
107	Stephen McDougle	MEI Technologies, Inc. (consultant to NASA White Sands Test Facility)
108	Kyle McKeown	The Linde Group
109	Noah Meeks	Southern Company
110	Nguyen Minh	University of California, San Diego
111	Cortney Mittelsteadt	Giner, Inc.
112	Miguel Modestino	New York University
113	Pietro Moretto	European Commission Joint Research Centre (JRC)
114	Syed Mubeen	University of Iowa

No.	Name	Organization
115	Christopher Muhich	Arizona State University
116	Rangachary Mukundan	Los Alamos National Laboratory
117	Deborah Myers	Argonne National Laboratory
118	Tien Nguyen	Independent
119	William Notardonato	NASA Kennedy Space Center
120	James O'Brien	Idaho National Laboratory
121	Robert Oesterreich	Air Liquide
122	Tadashi Ogitsu	Lawrence Livermore National Laboratory
123	Gregory Olson	CSRA Inc. (consultant)
124	Pinakin Patel	T2M Global
125	Matthew Pellow	Electric Power Research Institute (EPRI)
126	Michael Penev	National Renewable Energy Laboratory
127	Mike Perry	United Technologies Research Center (UTRC)
128	Michael Peters	National Renewable Energy Laboratory
129	Guillaume Petitpas	Lawrence Livermore National Laboratory
130	Joseph Pierre	KeyLogic Systems, Inc.
131	Peter Pintauro	Vanderbilt University
132	Bryan Pivovar	National Renewable Energy Laboratory
133	Karen Quackenbush	Fuel Cell and Hydrogen Energy Association
134	Glenn Rambach	California State University, Bakersfield/Third Orbit Power Systems, Inc.
135	Jeffrey G. Reed	University of California, Irvine
136	Joel Rinebold	Connecticut Center for Advanced Technology, Inc.
137	Tommy Rockward	Los Alamos National Laboratory
138	Ian Rowe	U.S. Department of Energy
139	Tecle Rufael	Chevron Energy Technology Company
140	Mark Ruth	National Renewable Energy Laboratory
141	Christian Sattler	German Aerospace Center (DLR)
142	Troy Semelsberger	Los Alamos National Laboratory
143	Alexey Serov	University of New Mexico, Center for Emerging Energy Technologies/Pajarito Powder, LLC
144	Kevin Simmons	Pacific Northwest National Laboratory
145	Joshua Snyder	Drexel University
146	Petros Sofronis	University of Illinois at Urbana-Champaign/International Institute for Carbon-Neutral Energy Research (I^2CNER)
147	Herie Soto	Shell Oil Company
148	Jacob Spendelow	Los Alamos National Laboratory
149	Vojislav Stamenkovic	Argonne National Laboratory
150	Andy Steinbach	3M
151	Nadia Steiner	Université de Franche-Comté
152	Jeff Stevenson	Pacific Northwest National Laboratory
153	Gary Stottler	General Motors
154	Jean St-Pierre	University of Hawaii, Manoa/Hawaii Natural Energy Institute
155	Scott Swartz	Nexceris, LLC
156	Karen Swider-Lyons	U.S. Naval Research Laboratory
157	Sandy Thomas	Clean Car Options (retired)
158	Mark Toughiry	U.S. Department of Transportation
159	Hiroshi Tsuchiya	New Energy and Industrial Technology Development Organization (NEDO)
160	Michael Ulsh	National Renewable Energy Laboratory
161	Hiroyuki Usuda	New Energy and Industrial Technology Development Organization (NEDO)

No.	Name	Organization
162	Nicholas Vanderborgh	Los Alamos National Laboratory (retired)
163	Mike Veenstra	Ford Motor Company
164	Laura Verduzco	Chevron Corporation
165	George Walchuk	ExxonMobil Research and Engineering Company
166	James Waldecker	Ford Motor Company
167	Adam Weber	Lawrence Berkeley National Laboratory
168	Jan Wegener	NOW GmbH
169	Douglas Wheeler	DJW Technology, LLC
170	Mark Williams	AECOM/National Energy Technology Laboratory
171	Stephen Woods	NASA
172	Hui Xu	Argonne National Laboratory
173	Piotr Zelenay	Los Alamos National Laboratory
174	Junliang Zhang	Shanghai Jiao Tong University (SITU)
175	Jonathan Zimmerman	Sandia National Laboratories
176	Barr Zulevi	Pajarito Powder, LLC

Summary of Peer Review Panel's Crosscutting Comments and Recommendations

AMR panel members provided comments and recommendations regarding selected DOE hydrogen and fuel cell projects, overall management of the Hydrogen and Fuel Cells Program, and the AMR peer evaluation process. The project comments, recommendations, and scores are provided in the following sections of this report, grouped by sub-program. Comments about Program and sub-program management are provided in Appendix A.

Analysis Methodology

A total of **116** Fuel Cell Technologies Office (FCTO) projects were reviewed at the meeting. As shown in the table above, **176** review panel members participated in the AMR process, providing a total of **665** project evaluations. These reviewers were asked to provide numeric scores (on a scale of 1–4, including half-point intervals, with 4 being the highest) for five aspects of the work presented. Sample evaluation forms are provided in Appendix C. Scores and comments were submitted using laptops (provided on-site) to a private online database, allowing for real-time tracking of the review process. A list of projects that were presented at the AMR but not reviewed is provided in Appendix D.

For the Hydrogen Fuel R&D; Fuel Cell R&D; Technology Acceleration and Hydrogen Infrastructure R&D; Safety, Codes and Standards; and Systems Analysis sub-programs, scores were based on the five criteria and weights provided below. The Hydrogen Fuel R&D sub-program includes two project categories: Hydrogen Production and Delivery R&D and Hydrogen Storage R&D; these were similarly evaluated.

Score 1: Approach to performing the work (20%)
Score 2: Accomplishments and progress toward overall project and DOE goals (45%)
Score 3: Collaboration and coordination with other institutions (10%)
Score 4: Relevance/potential impact on DOE Program goals and RD&D objectives (15%)
Score 5: Proposed future work (10%)

For each project, individual reviewer scores for each of the five criteria were weighted using the formula in the box below to create a final score for each reviewer for that project. The average score for each project was then calculated by averaging the final scores for individual reviewers. The individual reviewer scores for each question were also averaged to provide information on the project's question-by-question scoring. In this manner, a project's final overall score can be meaningfully compared to that of another project.

Final Overall Score = [Score 1 x 0.20] + [Score 2 x 0.45] + [Score 3 x 0.10] + [Score 4 x 0.15] + [Score 5 x 0.10]

A perfect overall score of “4” indicates that a project satisfied the five criteria to the fullest possible extent; the lowest possible overall score of “1” indicates that a project did not satisfactorily meet any of the requirements of the five criteria.

This year, the Hydrogen Production and Delivery R&D category included a sub-category for HydroGEN seedling projects. The evaluation form for these projects (included in Appendix C) was modified to address their unique features; the scores for these projects were based on the following five criteria and weights:

Score 1: Approach to performing the work (20%)
Score 2: Relevance/potential impact on DOE Program goals and RD&D objectives and the HydroGEN Consortium mission (15%)
Score 3: Accomplishments and progress toward overall project and DOE goals and the HydroGEN Consortium mission (30%)
Score 4: Collaboration effectiveness with HydroGEN and, as appropriate, other institutions (25%)
Score 5: Proposed future work (10%)

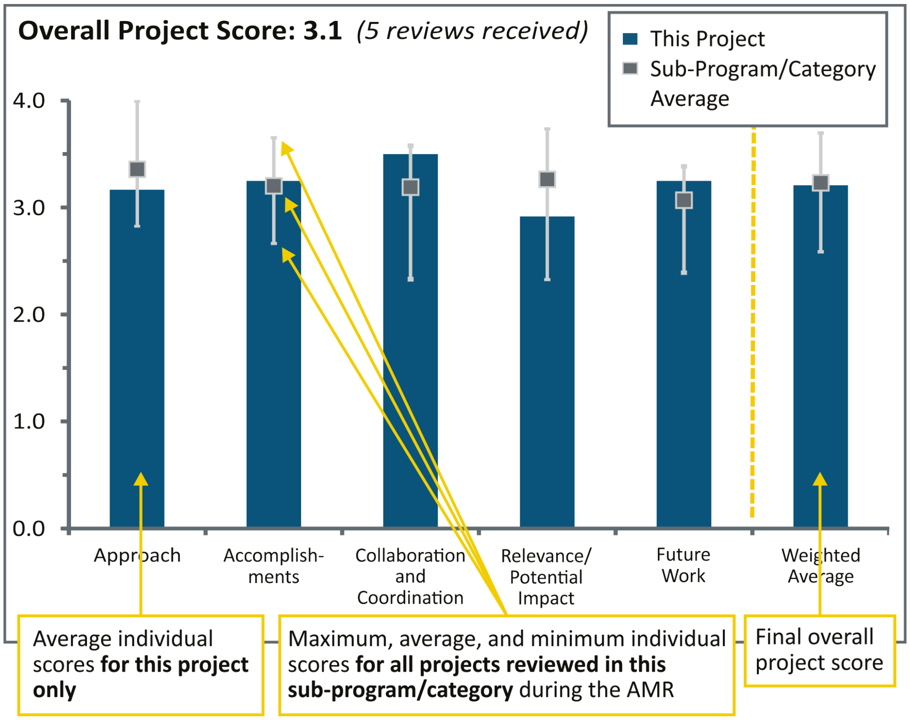
For all projects, reviewers were also asked to provide qualitative comments regarding the five criteria, specific strengths and weaknesses of the project, and any recommendations relating to the work scope. These comments were also entered into the private online database for easy retrieval and analysis.

Organization of the Report

The project comments and scores are grouped by sub-program (Hydrogen Fuel R&D; Fuel Cell R&D; Technology Acceleration and Hydrogen Infrastructure R&D; Safety, Codes and Standards; and Systems Analysis) and, in the case of Hydrogen Fuel R&D, by (sub)category (Hydrogen Production and Delivery R&D, HydroGEN Seedling, and Hydrogen Storage R&D) to align with FCTO’s planning scheme. Each of these sections begins with a brief description of the general type of research and development or other activity being conducted. Next are the results of the reviews of each project presented at the 2018 AMR, with a summary of the qualitative comments for each project.

Each individual project summary also includes a graph showing the overall project score and a comparison of how each project aligns with all of the other projects in its sub-program or (sub)category. Projects are compared based on the consistent set of criteria listed above. Each project report includes a chart with bars representing that project’s average scores for each of the five designated criteria. The gray vertical hash marks that overlay the blue bars represent the corresponding maximum, average, and minimum scores for all of the projects in the same sub-program. A sample graph is provided.

Sample Project Score Graph with Explanation



For clarification, consider a hypothetical review in which only five projects were presented and reviewed in a sub-program. Table 2 displays the average scores for each project according to the five rated criteria.

Table 2: Sample Project Scores

	Approach (20%)	Accomplishments (45%)	Collaboration and Coordination (10%)	Relevance/ Potential Impact (15%)	Future Work (10%)
Project A	3.4	3.3	3.3	3.2	3.1
Project B	3.1	2.8	2.7	2.7	2.9
Project C	3.0	2.6	2.7	2.8	2.9
Project D	3.4	3.5	3.4	3.2	3.3
Project E	3.6	3.7	3.5	3.4	3.4
Maximum	3.6	3.7	3.5	3.4	3.4
Average	3.3	3.2	3.1	3.0	3.1
Minimum	3.0	2.6	2.7	2.7	2.9

Using these data, the chart for Project A would contain five bars representing the values listed for that project in Table 2. A gray hash mark indicating the related maximum, average, and minimum values for all of the projects in Project A's sub-program or (sub)category (the last three lines in Table 2) would overlay each corresponding bar to facilitate comparison. In addition, each project's criteria scores would be weighted and combined to produce a final, overall project score that would permit meaningful comparisons to other projects. Below is a sample calculation for the Project A weighted score.

Final Score for Project A = [3.4 x 0.20] + [3.3 x 0.45] + [3.3 x 0.10] + [3.2 x 0.15] + [3.1 x 0.10] = 3.3

2018 – Hydrogen Fuel R&D
Summary of Annual Merit Review of the Hydrogen Fuel R&D Sub-Program

Summary of Hydrogen Fuel R&D Sub-Program and Reviewer Comments:

The Hydrogen Fuel R&D sub-program comprises early-stage research and development (R&D) to reduce the cost and improve the reliability of technologies used to produce, deliver, and store hydrogen from diverse domestic energy resources. The sub-program is divided into two categories: (1) Hydrogen Storage R&D and (2) Hydrogen Production and Delivery R&D. The latter includes seedling projects under the Hydrogen Generation Consortium (HydroGEN), which is part of the U.S. Department of Energy (DOE) Energy Materials Network (EMN).

In fiscal year (FY) 2018, production projects focused primarily on early-stage R&D for advanced water-splitting materials and systems funded through HydroGEN. Production pathways under investigation included advanced high- and low-temperature electrochemical water splitting, and direct solar thermochemical (STCH) and photoelectrochemical (PEC) water splitting. In FY 2018, delivery projects focused on liquefaction technology; materials compatibility research for infrastructure applications, such as pipelines; research on compression technologies, such as linear motor reciprocating compressors, metal hydride compression, electrochemical compression, and coatings for compressor seals; and hydrogen dispensing technologies, such as wireless communication, meters, and hoses. Hydrogen storage projects in FY 2018 focused on materials-based hydrogen storage R&D through the Hydrogen Materials—Advanced Research Consortium (HyMARC). HyMARC is an EMN consortium comprising a core national laboratory team and individual seedling projects that benefit from access to the core team's capabilities. The sub-program continued early-stage R&D in advanced tanks through development of precursor fibers for low-cost carbon fiber. All projects under the Hydrogen Fuel R&D sub-program continued to be evaluated with respect to their potential to meet DOE's cost and performance targets for the near and long terms.

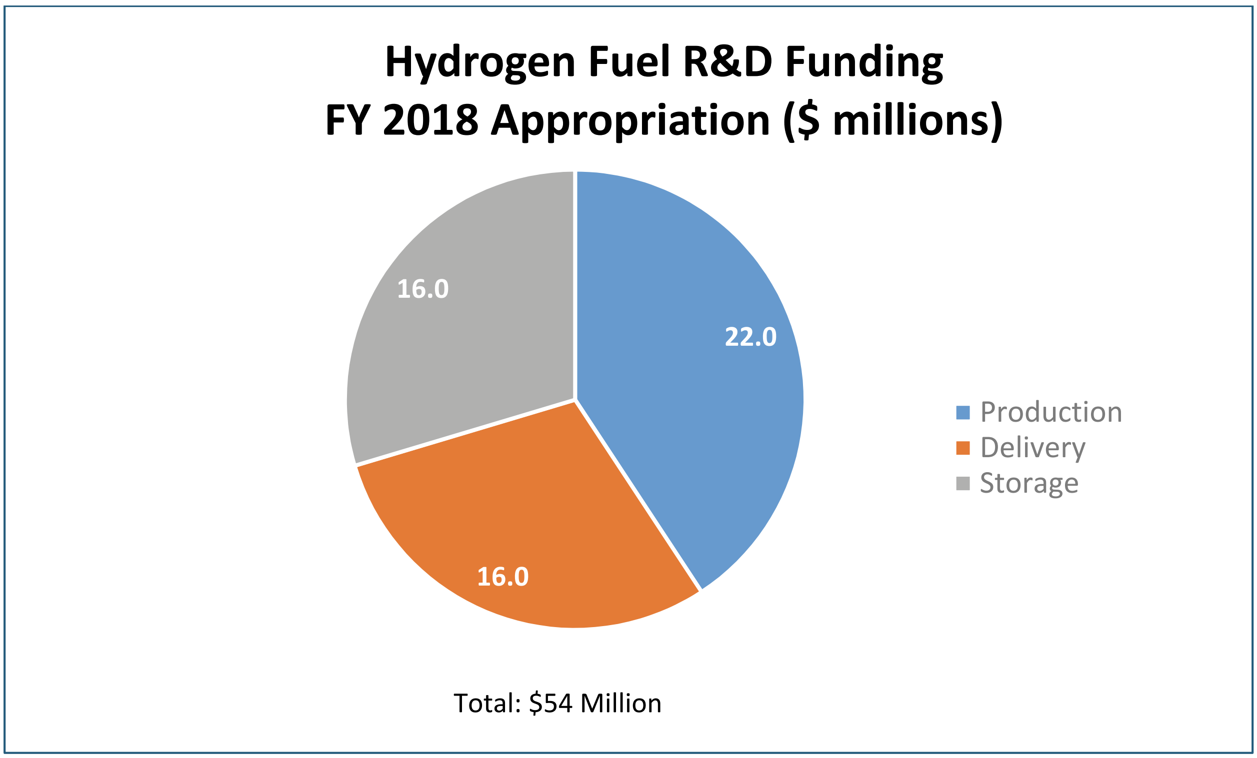
For the hydrogen production projects in the sub-program, reviewers were impressed with the effective collaboration of the HydroGEN Consortium and its cogent use of networking and productivity enhancement tools such as the shared data hub. The seedling water-splitting projects funded in conjunction with HydroGEN were praised for their strong interaction and successful leveraging of national laboratory capabilities through the HydroGEN framework. Reviewers were also impressed with the use of modeling and technoeconomic analysis efforts to guide experimental work toward meeting DOE cost targets. Reviewers commented that they would like to see increased interaction between the projects themselves as they move forward. Among hydrogen delivery projects, research on pipeline materials compatibility to enable large-scale infrastructure was particularly commended. Projects with research on electrochemical and/or metal hydride compression were praised for their potential to achieve higher reliability than conventional mechanical concepts, but the project teams were encouraged to consider the economic viability of these approaches. Projects on hydrogen dispensing were encouraged to collaborate with relevant industry stakeholders and ensure that technology prototype development is informed by early-stage materials research (e.g., materials compatibility evaluation and modeling of hose prototype performance). Fueling technologies for heavy-duty vehicles were recommended as an area for future research.

Within the hydrogen storage portfolio, reviewers noted an adequate balance of resources, priorities, and technical goals. Given the new focus on the H2@Scale efforts within the Hydrogen and Fuel Cells Program (the Program) as a whole, reviewers encouraged closer integration of early-stage R&D efforts, including hydrogen storage R&D, with H2@Scale infrastructure activities to maximize R&D impact and increase the likelihood of success for the overall Program. Reviewers commended the sub-program's management and openness to engagement, communication, and collaboration with stakeholders to ensure R&D work remains valuable to industry and relevant to the hydrogen and fuel cell market. HyMARC continued to be regarded as a key endeavor to leverage foundational scientific understanding and world-class resources and facilities across multiple institutions. The consortium was also recognized as a catalyst for groundbreaking advances in hydrogen storage materials with the potential to meet the sub-program's ultimate goals. As more HyMARC seedling projects are selected, reviewers encouraged continued and careful coordination across the HyMARC portfolio to prevent overlap in activities and maximize results.

Hydrogen Fuel R&D Funding:

The FY 2018 appropriation for the Hydrogen Fuel R&D sub-program totaled $54 million. Of these appropriations, $22 million was allocated for hydrogen production research, $16 million for hydrogen delivery research, and $16 million for hydrogen storage research, as shown in the figure below. Projects funded in the hydrogen production R&D portfolio are expected to accelerate materials development for advanced water-splitting technologies toward meeting DOE targets, and this emphasis is expected to continue into FY 2019. Nineteen hydrogen production projects were reviewed, with overall favorable scores ranging from 2.9 to 3.7, with 3.4 as the average score. Funding in hydrogen delivery focused on hydrogen pre-cooling technologies (e.g., cryocoolers), compression technologies, liquefaction technologies, and launch of the H-Mat consortium focused on materials compatibility research. Fourteen projects were reviewed, with a minimum score of 2.8, a maximum score of 3.6, and an average score of 3.3. In FY 2019, H-Mat is expected to remain a priority area of research. The hydrogen storage R&D portfolio was represented by twelve oral presentations and eighteen posters (including three Small Business Innovation Research [SBIR] projects) in FY 2018. Out of the twelve projects reviewed, nine focused on materials development, two on analysis, and one on engineering. In general, the reviewers' scores for the projects were good, with scores of 3.6, 3.1, and 3.4 for the highest, lowest, and average scores, respectively.

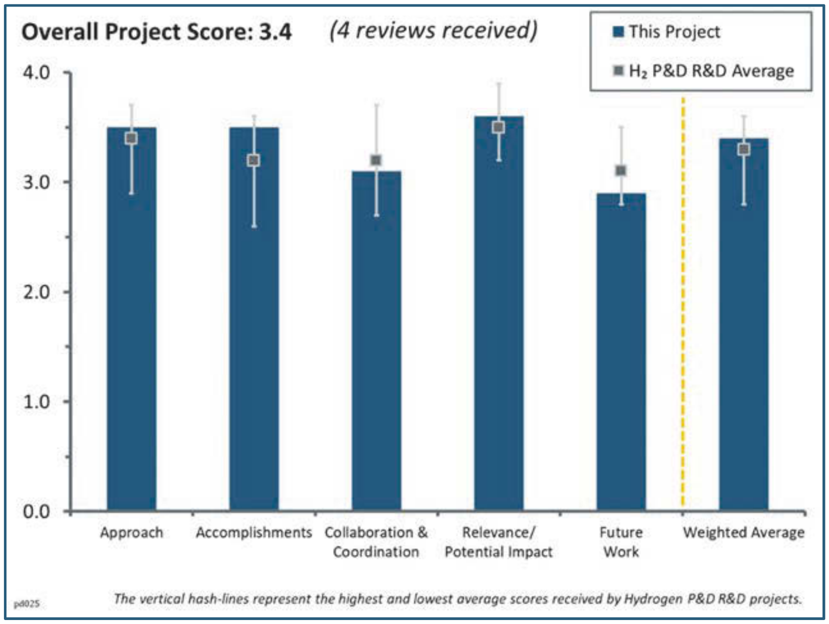
Each of the following project reports contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.



Project #PD-025: Fatigue Performance of High-Strength Pipeline Steels and Their Welds in Hydrogen Gas Service

Joe Ronevich; Sandia National Laboratories

Brief Summary of Project:



The primary objective of this project is to evaluate the potential for modern, high-strength steels to facilitate reductions in the cost of hydrogen pipelines. Specific goals are to (1) characterize fatigue performance of high-strength girth welds in the presence of hydrogen gas and compare performance to that of low-strength pipe welds, and (2) establish models that predict pipeline behavior as a function of microstructure in hydrogen to inform future development.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The experimental evaluation of the resistance of high-strength pipeline steel welds to fatigue crack growth is necessary for cost reduction. Similarly, an understanding of how this resistance relates to materials microstructure will lead to the development of steels with improved resistance. Consideration of the residual stress contribution shows a careful approach to the project objectives. The phenomenological model used to ascertain fatigue crack growth behavior needs further evaluation because it is not predictive.
- The goals of the work were clearly identified, and the project has a rigorous approach to achieve these goals. The lone consideration here is the concern that the fatigue crack growth rate (FCGR) testing is focused on the weld material; a further justification of the "weakest" link plane along the weld would provide more confidence that this approach is capturing the most relevant properties for failure.
- The project's approach is clear, logical, and detailed. The identification of actionable results and how to adapt those results into commercial practices would be helpful.
- The presenter provided a clear procedure for starting and completing the project.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The results could clearly lead to achieving DOE hydrogen delivery cost goals. For example, the finding that "using X100 (instead of X52) can result in 42% cost reduction for 24' pipe operated at 110 bar (1600 psi)" seems significant.
- Relevant data has been collected, important experiments linking microstructure to properties have been performed, and logical modeling approaches have been put forth. In all, the project has made strong progress toward the stated goals.
- All experimental results of the project were well presented. In particular, the result shown on slide 8 in which the behavior of the X100 steel is shown to be the same as that for low-strength steels is impressive. There is a problem with the result shown on slide 13; the numerically calculated stress ahead of the crack tip is not compatible with small-scale yielding behavior, and as such, it cannot scale with the stress

intensity factor associated with the compact tension specimen. Hence, the numerical results presented are not transferrable because of the absence of similarity. The comment on the slide regarding infinite and finite domain is irrelevant. It is not clear why the synchrotron studies shown on slide 14 are necessary. Evaluating elastic strains in a fracture specimen is just an elastic calculation.
- The materials are suited for hydrogen storage, not for transport.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- Strong research community collaboration was shown. However, industry and company-specific engagement was not presented.
- The collaboration with the University of California, Davis, on residual stress assessment is important.
- The collaborations within this project are adequate.
- This project has strong collaboration with other team members, particularly with the National Institute of Standards and Technology and University of Arizona. It is not clear that the results from the collaboration with Oak Ridge National Laboratory have yielded any insights, considering the lack of relevance of the elastic field results at scales that are relatively large, compared to the relevant plasticity-driven damage mechanisms in the micron-to-submicron size scale relevant to the hydrogen embrittlement damage process. Also, while there is scientific interest in understanding/modeling the role of microstructure in the hydrogen embrittlement damage process for these steels, it is important to ensure that the modeling is focused on a relevant question. The data (particularly the results on slides 8 and 9) show that the growth rates are generally agnostic to the microstructure (this is consistent with literature); as such, it is necessary to better justify the relevance of microstructure-scale modeling for this project.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The use of existing infrastructure (such as existing steel pipelines) for hydrogen transport/storage will be critical in the integration of this technology. Furthermore, the efficiencies gained by the use of higher-strength steels would be critical; such work is relevant to the qualifications of such ideas.
- This research is central to achieving DOE hydrogen delivery cost goals.
- The experimental component of the project is extremely important and impactful. It is difficult to assess the impact of the modeling work, as it relies on a phenomenological fatigue crack growth model.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed future work to develop test protocols to measure fracture toughness of welds and heat-affected zones and to broaden this project to influence other steels used in hydrogen infrastructure is valid and important. The project team could consider developing a commercialization roadmap.
- The proposed future work has good potential for the storage of gaseous hydrogen.
- Further correlation between grain size/FCGR would be interesting. In particular, identifying the relevant grain structure feature, as well as how/why this does/does not scale across different steel microstructures would be interesting. While the orientation-dependent trends observed on slide 10 are convincing, it is unclear why similar trends are not observed on slide 9. The additional Gleeble specimens will be useful in identifying this. The calibration of the diffusivity measurements is tricky. As always, it is hard to understand the transfer function between bulk diffusivity metrics and diffusion through a highly dislocated structure at the crack tip. The project team's publishing goals are good.
- The proposed work on slide 16 is all descriptive, without a single explanation. The presentation did not clarify how single-grain response could be related to the FCGR (da/dN) versus the change in stress

intensity factor (dK) curves for welds. In addition, the presentation did not clarify how the hydrogen effect would be treated in the modeling of the single-crystal response.

Project strengths:

- This is a relevant topic with a good approach and good progress, led by a team with the appropriate expertise to address issues. This is a unique and rigorous experimental effort. It incorporates residual stress into the driving force calculations. The work also consists of unique correlations of microstructure and FCGR behavior; there is a strong link between the scientific work and a useful engineering output via informing the governing specification.
- Strengths include:
    - Remarkable experimental findings
    - Actionable results for hydrogen pipe materials that can be expanded to other materials
    - A plan for peer-reviewed publication of results
- This project's strength lies in the experimental evaluation of fatigue crack growth of high-strength welds.

Project weaknesses:

- There are no material weaknesses.
- There is tenuous relevance of the diffraction work on the technical topic and a lack of consistency between the effects of grain boundaries for the different orientations, as well as a lack of impact of the boundaries for the Gleeble material. Better justification for the microstructure-scale modeling is necessary when the data shows that the FCGR behavior is agnostic to the microstructure. There is work to be done here, but the concern should really be about why there are similar growth rates despite changes in strength (thus the nature of the local crack tip stress gradient) and diffusivities between the different materials that would lead to different crack tip stresses and H-profiles. It would be good to know whether the model can predict this, as well as predict instances where this may not be the case. Technical concerns include the following:
    - The project needs to establish whether it is the weld metal or the heat-affected zone (or another part of the weld) that will actually fail if the team were to run a dog-bone sample in this orientation. This leads to the question of the rigor of putting the notch in the weld metal, rather than at another part along the weld. This will be even more important in the next phase of the work if fracture toughness is evaluated.
    - As one incorporates the residual stress into the dK calculation, the maximum thermal performance (R–value) will inherently change. However, the magnitude of R-value change is not stated. It is unclear if the R-value could be pushed low enough to the point where it becomes relevant (owing to closure of other R-dependent mechanisms).
    - It is unclear why the grain-dependent behavior is seen for the orientation but not for the Gleeble. The exact meaning of high-angle grain boundary (HAGB) is not clarified. It is also unclear whether these are prior austenite grains.
    - Recent work on strain gradient plasticity suggests that the local stresses that were calculated in figure 13 may be too low and too diffused. These calculations are qualitatively consistent with the abundance of crack wake transmission electron microscopy (TEM) analysis that shows a highly localized dislocation structure focused within roughly one micron of the crack wake. It is important to consider/refute this as the current models are interpreted.
    - The assertion that the growth rates outrun the diffusivity was not clearly articulated.
    - It was not clear how the project team monitored the crack length during the work on the Gleeble sample. If this was done via compliance, then it is unclear if there is any concern about inhomogeneity within the bulk compliance as the crack progresses because of the gradient in the microstructure. The sensitivity of the results to such an effect is unknown.
    - There are many issues with the superposition model reported in figure 11. This is a criticism not of the project but rather of the relevance of having such a model in a standard.
    - The devil is in the details on slide 16. The incorporation of the environmental–mechanical aspects of the loading into the X-face is not explained.
- The modeling and simulation within this project is very general and not targeted to the specific characteristics of the weld microstructures.

- This project's approach is not practical for the transportation of high-pressure hydrogen because of the excess weight of thick steel wall pressure vessels.

Recommendations for additions/deletions to project scope:

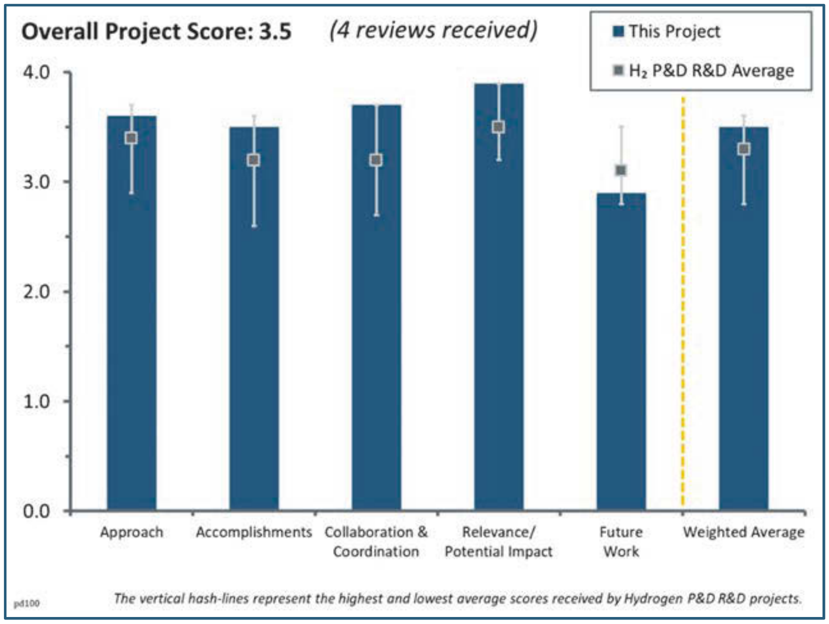
- Understanding weld microstructures experimentally is a very important objective and needs to be pursued. The synchrotron studies are irrelevant to the project and have not revealed anything related to fatigue crack growth.
- One important addition to the project scope could be the development of a field demonstration to validate cost savings and performance. This could help drive the adoption of improved practices based on the research results.
- The modeling effort should be focused to better align with the observed data trends. The diffraction work should be either eliminated or repurposed.
- It is recommended that the team look for other materials, such as carbon composite.

Project #PD-100: 700 bar Hydrogen Dispenser Hose Reliability Improvement

Kevin Harrison; National Renewable Energy Laboratory

Brief Summary of Project:

The objective of this project is to characterize and improve 700 bar refueling hose reliability under fueling conditions expected at heavily utilized hydrogen fueling stations. The National Renewable Energy Laboratory designed a test system that subjects refueling hose assemblies to pressure, temperature, mechanical, and time stresses. The high-cycling test reveals the compounding impacts of high-volume 700 bar fuel cell electric vehicle (FCEV) refueling, which has yet to be experienced in today's low-volume market.



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project team identified an issue of clear importance to hydrogen infrastructure, especially in early days of rollout, in that dispenser hose failure will have an impact on not only station economics but reliability and therefore customer experience. The team has adopted a good approach to investigating the problem by using both accelerated testing and post-mortem analysis.
- The project is very relevant and directly applicable to industry needs. Hoses are a common failure point and a high-cost maintenance item, owing to frequency. More importantly, public safety is directly affected. The capability this project provides is appreciated; Shell intends to leverage this project.
- The testing facility and protocols are outstanding.
- Using a six-axis robot that emulates human motion when interacting with the hose, the duration of fills, and the pressure profile did real interactions justice. However, it would be desirable to address different ambient temperatures, as it is to be expected that temperature shocks are more severe in different environments. Therefore, the impact of temperature shocks could have been discerned more precisely.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Good failure mode analysis was provided, helping to inform new product development to solve reliability issues and reduce cost.
- The project has covered all objectives: testing and detailed identification of failure.
- The progress that has been made on the specific hose tested is significant. It remains a little unclear what was responsible for the surface blistering (i.e., the plastic failure) and what polymers might solve the problem. For future progress, it would be nice to include a hose other than the one from SpirStar to be able to draw inferences from different hose designs (e.g., different wire braidings or steel overwraps).

- The project should significantly increase the number of post-mortem analyses in order to assess type and frequency of failure modes. If these hoses have indeed been failing at high rates, there should be plenty to examine.

Question 3: Collaboration and coordination

This project was rated **3.8** for its collaboration and coordination with other institutions.

- Other research institutes working on the problem from another angle are part of the cooperation. The issue of integrating another hose supplier has been addressed. Especially remarkable is the cooperation with the International Organization for Standardization's Technical Committee 197, Working Group 22 (ISO/TC 197/WG 22).
- There is excellent collaboration with industry and suppliers to test the most relevant products and share operational experience.
- All collaborations shown on the relevant slide are outstanding, with each one serving a specific purpose.
- For the size of the project, there is an impressive list of collaborators making high-quality contributions. Expanding the list of hose providers is suggested.

Question 4: Relevance/potential impact

This project was rated **3.9** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Frequent hose failures will give hydrogen refueling stations a bad reputation. If this project is successful in developing a strategy to greatly increase hose reliability, the project will have a meaningful impact on the uptake of FCEVs by avoiding the development of negative interactions, and it will have done so at a modest cost. The potential impact-to-cost ratio is high.
- The project is already making measurable impact in practice. Shell has a focus on changing hose suppliers and possibly helping to develop a new product with suppliers. This project and the test facility are a large part of assisting suppliers to develop less expensive and more reliable solutions.
- There can be no doubt about the relevance, as hose failures are an issue for every hydrogen fueling station operator. Apart from nozzle failures, hose failures are the most common reason for hydrogen fueling station downtime, which undermines consumer trust and buy-in. A remedy to this problem, therefore, is badly needed.
- Having identified the way failure appears and advances, the project can identify mitigation strategies.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed activities in the future cover the most vital challenges, namely using a hose from a different manufacturer and using dynamic mechanical analysis (DMA) rheology. However, it would be desirable to also address different plastic composites in more detail, if that is possible. This may be an issue, as manufacturers may not be inclined to share such information, but it may be possible to ask them to provide different prototypes. In the future, different ambient temperatures in which the robot works should also be addressed in order to learn more about thermal shocks in very cold (as in winter in the Northeast) and hot (as in summer in California) conditions.
- The listed potential upgrades are worth pursuing, provided that the reasons for failure have been identified and analyzed.
- The project should be more ambitious in its plan for testing the polymeric materials used in hoses. Increasing focus on DMA at cold conditions is commendable, particularly if it will involve temperature cycling. However, the team should consider how it could combine temperature cycling with hydrogen pressure—if not in the DMA, because of technical or safety challenges, then in a separate test rig where a DMA sample could be exposed to temperature and hydrogen pressure cycling, then subsequently

tested in the DMA or other mechanical property testing for failure. The project team should consider also adding a notch or other controlled flaw to simulate the stress concentration from the steel wire overlap.
- Future steps were unclear.

Project strengths:

- This project is a good use of DOE funding to address a critical issue for hydrogen delivery. The research plan incorporates accelerated testing and post-mortem analyses. The focus was on understanding the root cause of failures. There was an appropriate focus on properties of construction materials and the influence of cycle conditions, especially thermal shock.
- This project is highly relevant. The testing design is excellent and innovative, emulating real-world conditions very well. The choice of partners/cooperators was outstanding.
- This project was well executed with good collaboration and is relevant for cost-reduction goals.
- The project has a systematic and well-thought-out experimental approach to testing.

Project weaknesses:

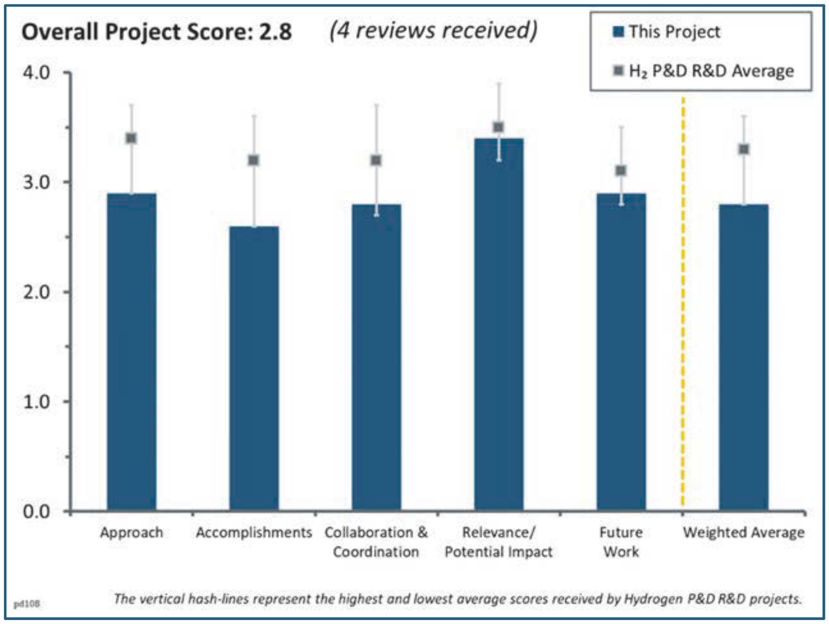
- There were hardly any weaknesses.
- There were not enough post-mortem analyses to date to really understand the range and frequency of failure modes. The materials property testing protocols need to be more creative to better expose those materials to temperature and hydrogen pressure cycles that can encourage growth of cracks and holes due to stress/strain.
- There was a lack of understanding of failure initiation and evolution.
- This project should be communicated widely to industry; not many know about it.

Recommendations for additions/deletions to project scope:

- The project should collaborate more closely with experts on hydrogen interactions with reinforced polymers. Observed failures need to be understood so that mitigation strategies can be suggested. A solid mechanics researcher with expertise in viscoplastic deformation and failure analysis should be added to the team.
- Japanese hoses should be included in the testing and post-mortem analysis plans, particularly if they use different materials.
- A focus on crimping and the effect this has on reliability would be an improvement.
- Increased variation in crucial parameters, which would provide the ability to draw inferences, would be good.

Project #PD-108: Hydrogen Compression Application of the Linear Motor Reciprocating Compressor

Eugene Broerman; Southwest Research Institute



Brief Summary of Project:

The objectives of this project are to (1) improve isentropic efficiency of high-pressure hydrogen compression above 95% by minimizing aerodynamic losses, (2) reduce capital costs to half those of conventional reciprocating compressors by minimizing part count, and (3) reduce required maintenance by simplifying the compressor design to eliminate common wear items.

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project is focused on compressor efficiency and cost, which are major challenges in hydrogen infrastructure.
- High-efficiency lower-cost hydrogen compressors are needed to reach hydrogen refueling cost goals.
- The approach needs to be more clearly defined. Listing milestones from three years ago does not help reviewers determine the approach to this year's work. The milestone list provides reviewers with an explanation of high-level tasks that have been completed, but the list is not clear about what was done this year versus past years. After looking up last year's U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review (AMR) presentation, it looks like all that needed to be completed this year was the test stand construction, commission, and bench-scale performance testing. It is unclear why these three tasks are not the focus of this presentation. It also is not clear why building the first low-pressure stage of the hydrogen compressor is the appropriate approach to building this three-stage compressor. The integration of the multiple stages along with the pressure requirements of the medium- and high-pressure stages is not trivial. The strategy to start with the low-pressure stage individually may be correct, but the project lead has not indicated why this is the case.
- The project takes a technical approach to device development.

Question 2: Accomplishments and progress

This project was rated **2.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The accomplishments are fine, given the goals and approach of the project.
- Improvements in speed, design, and sealing were implemented, but significant improvements in efficiency have not yet been made.
- A clear picture needs to be presented of this year's accomplishments, important discoveries, and innovations. Work from years ago and simple maintenance tasks should not be highlighted. There is a need to focus on progress around isentropic efficiency, motor control issues, and the completion of next steps.

The presentation was a disappointing highlight of what might otherwise be good work. Raw notes for each slide are provided for the project team to improve the presentation for next year.

- Slide 6 from AMR 2016 is not relevant to current progress.
- Slide 7 from AMR 2016 is not relevant to current progress.
- On slide 8, it is unclear why these components failed; perhaps they were sized improperly. It is uncertain what is the root cause of this failure was and whether there were lessons learned.
- Slide 9 is not an accomplishment—the content is neither interesting nor impressive.
- On slide 10, motor control would be essential to operation. The approach to remove the linear variable differential transformer (LVDT) and replace it with electromagnetic sensors seems reasonable, but unfortunately, it did not work. Solving this problem is essential to future success.
- On slide 11, it seems failures would be expected if the researchers knew they did not have full control of the motor. Given the inaccuracies in motor control, the graph provided looks okay. The number of measurements taken is unclear, and it is uncertain whether this is just n = 1. Multiple iterations could help smooth the data.
- Slide 12 states, "Commissioning issues sufficiently resolved," but how and when are not explained. It is uncertain whether motor control is still an issue. The approach of designing the first test to be able to make changes and pack later is good.
- The results on slide 13 look good and have finally hit one of the main components of the project, which is a high isentropic efficiency. More details are needed on how the 80%–90% isentropic efficiency is calculated and how many tests were performed to get to this efficiency. The compression ratio will need to increase for the other stages.
- Backup slides 30 and 31 indicate that LVDT and motor control are still an issue and that they have not been solved. It is not stated whether the data provided are only from short-duration tests that ensure damage to the compressor does not happen.

- Accomplishments over the previous year seem modest. The flow rate has not met the 10 kg/hour ±10% target, but the efficiency appears as though it will meet the target (>73%). Much like the responses to last year's reviewers' comments, concerns remain over the efficiency. It appears as though there is significant work remaining regarding (re)design, purchases, controls, and testing. It is not clear whether the remaining budget is sufficient for the remaining efforts.

Question 3: Collaboration and coordination

This project was rated **2.8** for its collaboration and coordination with other institutions.

- The new partner, Libertine, is expected to help solve significant remaining feedback and control challenges.
- The collaborations shown on slide 15 seem to be okay.
- The project team has done an okay job of utilizing their collaborations. The team needs to focus on leveraging Libertine to achieve high efficiency moving forward. A project partner that can help solve the motor control issue is needed.
- The collaborations with part and component suppliers and partners are very good, but the project lacks collaboration with potential users of the linear compressor.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Lower-cost, low-maintenance hydrogen compression is essential to offering hydrogen to fuel cell vehicles at a competitive price.
- If this project is successful, the compressor could help reduce the burden of compressor reliability that exists today.
- The project team discussed how they would get their three-stage design down to 2.54 kWh/kg, which is approaching the Multi-Year Research, Development, and Demonstration Plan target of 1.6 kWh/kg. The team needs to leverage Libertine to achieve this. The original design and concept is there, but the progress

is lacking. A high-efficiency hydrogen compressor that could get up to 875–900 bar would have a big impact on the industry.
- The project is relevant, but it is not certain that it will lead to viable technology for real-world hydrogen compression.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- It appears the project team understands the challenges ahead and is set to take them on. The detailed challenges and barriers section was appreciated.
- The proposed future work is in line with the approach.
- It would be nice to quantify this particular motor's energy consumption (as indicated on the Proposed Future Work slide) in comparison with the 1.6 kWh/kg and include the starting and ending pressure.
- The provision of more detailed steps toward achieving the project targets is desired.

Project strengths:

- The unique and novel design of this compressor is intriguing. It is focused on compressor costs, which are a burden on the deployment of hydrogen systems.
- The project compressor has a simpler design and higher efficiency compared to conventional reciprocating compressors.
- The project goals are in line with industry needs, and accomplishments around the isentropic efficiency look promising.
- The design proposed in this project can lead to real-world technology.

Project weaknesses:

- The safety and safe operation of the test rig is a concern. Slide 9 shows a leaky pressure safety or relief valve found with a Snoop liquid leak detector on a (relatively) low-pressure nitrogen fitting. It is great that the leaks were found, but the label pressure safety valve (PSV) 100 (product specification to 500 psi) does not match the ink-pen-written setpoint of 1360 psi on the side of the valve body. The purple wrap on the PSV seems to confirm the ink-pen setpoint is within the range of the Swagelok PSV spring set, so the label needs to be changed to read PSV 130. This seems petty, but for an owner/operator of hydrogen systems at pressures approaching 13,000 psig, attention to detail is critical, and documentation (even labels) helps reduce the chance of accidents.
- Material failures in the presence of hydrogen (e.g., valves and seals) are likely to occur, but the project does not address those failures.
- Durability testing is not addressed.
- The project team should focus on what is important to the project and reporting to industry. If slides from previous AMRs are used, they should be marked accordingly.

Recommendations for additions/deletions to project scope:

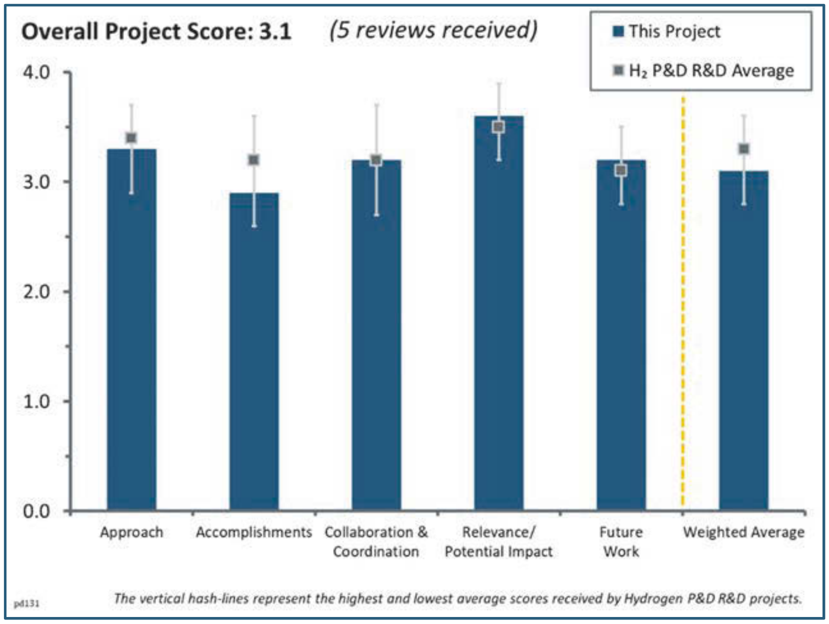
- The project team should focus on getting Stage 1 dialed in and what the plan will be to move to Stages 2 and 3 of the compressor. Issues around high pressure and how that will change compressor design should also be addressed.
- Durability testing must be added to validate component improvements.
- It is recommended the project team have an understanding of potential component failures and mitigation strategies.

Project #PD-131: Magnetocaloric Hydrogen Liquefaction

Jamie Holladay; Pacific Northwest National Laboratory

Brief Summary of Project:

The Pacific Northwest National Laboratory (PNNL) magnetocaloric hydrogen liquefaction system is expected to be considerably more energy-efficient than the Claude cycle. At 30 tons per day, the latter shows 40% efficiency, while the former is projected to be 70%–80% efficient. In this project, investigators will demonstrate the PNNL system liquefying ~25 kg/day. At industrial scales, the concept is expected to have a figure of merit (FOM) >0.5 (as compared to the Claude cycle system's FOM of <0.3). The project will also identify a pathway to a larger-scale system with an installed capital cost of less than $70 million.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project will develop a magnetocaloric process for liquefying hydrogen. These materials will couple with magnetic fields and operate as a solid-state refrigerant. Current technologies operate at less than 40% efficiency, have a capital cost of $70 million, and require 10–15 kWh/kg H_2. The project will achieve 60%–85% efficiency and operate at 5–6 kWh/ kg H_2. To achieve these metrics, the project will demonstrate magnetocaloric hydrogen liquefaction from 285 K for the first time at 10–25 kg/day. The project approach involves engineering and designing new installations with bypass flow, new ferromagnetic materials, and a 6T magnetic field. The two-stage design will lower hydrogen from 285 K to 120 K in the first stage, and finally to 20 K in the second stage.
- The team is looking at improving the baseline design by exploring bypass flow, different materials, and a magnetic field. The focus on starting from room temperature is fine, but a good deal of effort is being spent on a 70 K cooling system from room temperature, and it is of concern that much more trouble is ahead at cryogenic temperatures. This concern was expressed last year, but the principal investigator seems to be very confident that this will not be an issue. More science-/engineering-based arguments would have been welcome here.
- The approach is grounded on solid physical principles, and the team has identified problems with the current design (joule heating when the material moves into the magnetic field). The source of G-10 cracking was identified with the unexpected change of the coefficient of thermal expansion of the housing. However, the solution to the cracking problem was specific to the design under consideration and not a general approach to any future design developments.
- The approach has been reasonable, given the changes in plans because of development issues. Reducing the overall scope may be necessary for the team to achieve success by the end of next year.
- The demonstration of the concept is good. More work on the feasibility of the concept in practice would be helpful. It is not clear what the system to support the core concept looks like.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has the potential to drastically improve state-of-the-art technology for hydrogen liquefaction. An anticipated two- to three-fold decrease in energy input would reduce production costs and is better than the 2017 DOE target of 12 kWh/kg H_2.
- The project experienced some hiccups (G-10 cracking, valve design), which is totally understandable and well documented. The researchers were proactive in addressing those issues, and FOM analysis was a great addition to this work. A few concerns remain (on slide 20: the total ideal work and why its value differs from the first row are both unclear), including a comparison with today's benchmark, although this is partially addressed in the backup slides (slide 37). A detailed breakdown for both options, side-by-side, would be great.
- The team did a commendable job in making progress and overcoming technical hurdles. G-10 cracking due to large coefficient of thermal expansion (CTE) effects has been mitigated. The Ames Laboratory did a great job in potentially reducing the production costs of the magnetic materials. The addition and development of diversion valves was also noteworthy. The demonstration of bypass flow helps the efficiency of heat exchange, but more progress needs to be made in the magnetic refrigeration performance. It is unlikely that the full set of objectives will be achieved by the end of fiscal year (FY) 2019.
- The presenter claimed that the FOM for the device was 0.73 and that bypassing reduces it to ~0.5. No explanation was given for such a high FOM. It is not clear how such an extraordinarily large FOM can be achieved with the project's design, which involves two heat exchangers. In addition, the presenter's argument on low cost, despite the use of rare earth metals, needs further elucidation.
- It is unclear whether this approach will be cheaper/smaller/more responsive/etc. than current liquefaction approaches. It was not clear what the targets for this technology were.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- The project team ran into trouble in 2017 when the system experienced mechanical failure. A crack developed in the regenerator housing during the cool-down process. The FY 2018 work was then refocused to address this problem. It was determined that a force imbalance associated with the movement of magnetic material in and out of the magnetic field contributed to the cracking. This problem has since been fixed by adding a flexible and expandable polytetrafluoroethylene (ePTFE) packing material between the layers and the housing. Additional work has addressed force imbalances. The magnetic field has been increased to 6T, and the cryogenic cooler has kept the magnet at ~5 K. First- and second-quarter milestones have been completed, including design and initial cool-down operation, achieving a 50 K temperature drop. New diversion valves were developed and constructed to control the flow between individual layers. No commercially available components were obtainable, so this required in-house fabrication. This new setup allowed for cooling down to 203 K. The design for the two-stage system has been completed.
- It looks like the work is going smoothly between the three main partners (PNNL, Emerald Energy NW, LLC. [EENW], Ames Laboratory). The Caloric Materials Consortium, CaloriCool (Energy Materials Network), seems to be another great avenue for collaborations.
- Collaboration with Ames Laboratory on materials issues is important.
- The longstanding partnership with Ames Laboratory and EENW is good. At some point, however, it would be good to see some private money being invested as matching funds.
- There was no collaboration (or it was not apparent) with industry; this is important for understanding the technical and commercial requirements for the technology. The project does have good collaboration among academia and institutions, however.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project has good collaboration with Ames Laboratory and Iowa State University for materials characterization and synthesis, as well as with EENW for design and modeling, experimental tests, and data/cost analysis. The project is also engaging the CaloriCool consortium to encourage development of new magnetocaloric materials.
- It is a potential game changer if high-FOM hydrogen liquefaction can be achieved via magnetocaloric refrigeration, since liquefaction costs are a major issue in commercial hydrogen usage. There is also a potential reliability benefit due to lack of moving or rotating equipment requiring lubrication.
- Small-scale liquefaction systems are very relevant for unlocking low-cost access to locally distributed, renewable hydrogen. An explanation of how this technology will achieve that (in terms of economics, permitting, footprint, plausibility, etc.) is necessary.
- Alternative techniques to liquefy hydrogen are necessary, and the active magnetic regenerator liquefier cycle certainly represents one of the best options thus far.
- The project is very important to the Hydrogen and Fuel Cells Program mission, but the claim of an FOM equal to 0.73 is difficult to believe. The investigators must present a solid and detailed quantitative argument to support such a claim.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work involves the validation of the multistage concept to reduce temperatures from 285 K to 120 K, and then from 120 K to 20 K. FY 2018 plans also involve engaging industrial partners, redesigning and testing the valve system, and designing and building an eight-layer system. FY 2019 plans involve testing the eight-layer stage to achieve 120 K and then having a final demonstration of 120 K to 20 K liquefaction. Finally, FY 2020 plans involve hydrogen gas liquefaction, completion of technoeconomic analysis (TEA), and the licensing of patented technology.
- It is very clear what the next steps are to overcome some of the challenges identified in this phase. This future work is certainly relevant for advancing the technology readiness level.
- The determination of the FOM must be an important part of the future plans of the project, especially as it relates to the new materials synthesis and the heat exchanger design.
- The proposed future works seem a little too optimistic. Given the troubles experienced thus far, it is likely that the Gen-3 design effort, including the heat exchanger and ortho/para catalyst, will be much more significant than anticipated. The project is expected to last only one quarter into FY 2020, but the project team expects to carry out a good deal of work within that timeframe. Refocusing the scope of work may be discussed with the Fuel Cell Technologies Office (FCTO).
- It appears the scope for the next year has been changed to focus only on the first stage. That is fine, as long as progress is being made. However, the second stage will be more challenging than the first. Perhaps the team might give some thought to doing an initial cooldown using liquid nitrogen (LN2) to get the magnets below the Curie temperature.

Project strengths:

- This project's main strengths lie in the promise of this technology to help minimize liquid hydrogen (LH2) costs and the simplicity and elegance of a magnetocaloric refrigeration system, as compared to typical cryogenic liquefaction cycles. Much good progress was made, both in advancing the original objectives, as well as in overcoming technical hurdles.
- The project has a knowledgeable team working on a complex and innovative technology that could be a game changer for hydrogen deployment. Issues are methodically addressed and include hands-on

demonstration and engineering solutions. This project should definitely keep being funded beyond the present contract.

- This is a very ambitious project that has the potential to transform hydrogen liquefaction. The project team has had some initial setbacks, but solutions have been found. The approach is unique.
- The project has a very compact liquefaction system and could be a very simple operation. The project also has a nice demonstration of applied engineering and science.
- The project's strengths lie in its technical design and industry and laboratory collaborations.

Project weaknesses:

- The setbacks associated with the initial cooling indicate additional unforeseen challenges in the future. This will likely require redesigns and possible delays. The project also relies on relatively expensive and rare materials, although the team does provide some evidence that less expensive magnetic materials could also work. It is unclear how scalable this technology is, but a full TEA may provide insight.
- The project team really needs to describe a vision for how this core technology would be integrated into a full system and what the commercial targets are for the technology. The team needs to explain the product/commercial challenges with the system. For example, the technology uses large amounts of rare earth materials; the team needs to address whether this is a problem.
- The presentation could be improved. Complicated phenomena should be expressed in simple ways for the public and reviewers to fully appreciate the work being performed. For example, the process flow diagrams on slide 18 are unnecessarily complex, with a small font. The diagrams look like the same figure pasted twice, with the only difference being the J-T valve.
- This is a very challenging technology, and DOE has been funding it on some levels since the early 2000s. After all this time, there are still challenges in achieving cryogenic temperatures, much less LH_2 temperatures.
- It is hard to accept the reported FOM magnitude of 0.73. The investigators must make a detailed presentation of how they came up with such an extraordinarily high FOM.

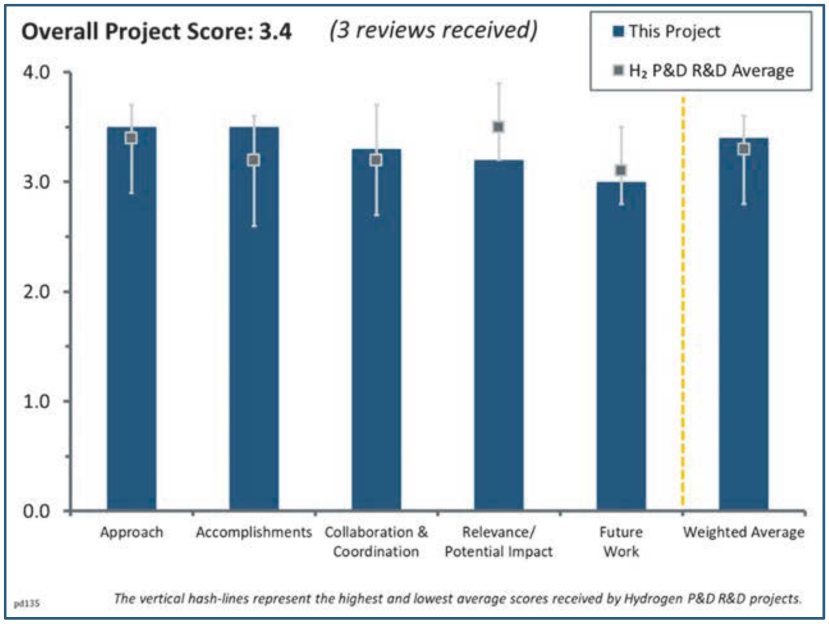
Recommendations for additions/deletions to project scope:

- No additions/deletions to the project scope are recommended. Perhaps the work should have been focused on cryogenic temperatures (e.g., LN_2) first for accrued learning, but it is too late now to re-scope the entire project. The project team demonstrated cooling/liquefaction to 230 K a couple of years ago, albeit using a much less efficient design.
- There should be more efforts made in the lower-temperature stage. This will be more challenging thermally, but the first stage can be approximated by a LN_2 supply.
- TEA should be considered in FY 2019 rather than FY 2020.
- It is recommended that the project team do more work on the system design.
- It is recommended that the team put more focus on the FOM.

Project #PD-135: Liquid Hydrogen Infrastructure Analysis

Guillaume Petitpas; Lawrence Livermore National Laboratory

Brief Summary of Project:



Liquid hydrogen (LH2) has many benefits for the hydrogen infrastructure, especially at large scale. However, the high cost of liquefaction, integration of LH2 with refueling stations, and transfer and boil-off losses pose challenges to broader use of LH2. This project aims to better understand and quantify the transfer and boil-off losses along the LH2 delivery pathway. To accomplish this, the project team simulated the LH2 pathway (from liquefaction plant to end use) using a thermodynamic model to estimate, then mitigate, the transfer and boil-off losses that occur at each step along the delivery pathway. Real-life driving and parking data were collected from a large population to use as an input for the model. The project also identified the major hydrogen boil-off sources and investigated potential recovery technologies and processes—from technical and cost perspectives—to eliminate and/or reduce these losses.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The research approach used was appropriate and led to a first-order analysis of the boil-off losses in handling LH2 fuel. The basic thermodynamic models allowed an improved understanding of the problems associated with using hydrogen fuel in liquid form, and resulted in recommendations that could significantly avoid boil-off losses. The project was well designed, and the scope was relevant to the goals of the Hydrogen and Fuel Cells Program and well aligned with H2@Scale activities.
- The development of models to simulate LH2 processes and losses is a valuable tool to help identify major loss mechanisms and evaluate the impact of changing systems.
- The modeling approach is a reasonable approach. However, it was not clear whether the model was validated. The project team had some data that could have been used to validate the model. It is not clear if the team used hydrogen recovery analysis to try to determine whether hydrogen purification was required. Since it is likely that the recovered hydrogen would require purification, the purification costs should have been added. The project team contacted two gas companies, which was good. However, they did not contact users such as NASA or refueling stations. Those users, especially NASA, might have provided much insight.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project accomplished the desired goals. A versatile model was constructed that allowed for the analysis of boil-off losses from liquefaction to car dispensing, as well as onboard. Furthermore, the project provided

guidelines within regulation that may result in significant hydrogen savings from not venting LH2 trailers. The model was used to simulate the performance with real driving patterns, and the conclusions indicate that, when handled appropriately, boil-off losses can be minimized to only a few percent of LH2 stored.
- It appears that all original technical objectives have been accomplished, and the models have been made available for others to use/validate.
- The analysis suggests that hydrogen boil-off losses were acceptable in most cases. The hydrogen recovery may not make economic sense, and the team did not examine whether there was a safety reason to recover the hydrogen. The identification of top-fill operation as a preferred mode is important. The boil-off recovery system could reduce the cost to end users by 50%.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- This is a small project, so major collaboration is difficult, but the principal investigator (PI) reached out to other government and industry experts to gather their feedback.
- The collaboration was fruitful, as evidenced from the positive outcome of the project.
- The project team engaged two gas companies. It is surprising that pump companies and companies using LH2 were not contacted. The team should have contacted companies who are currently using LH2, such as NASA and the many locations using LH2 for their hydrogen-powered forklift fleets.

Question 4: Relevance/potential impact

This project was rated **3.2** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The findings from this project will help inform the decision on pathways for hydrogen distribution. LH2 has high potential for economic savings from lower transportation costs, thanks to the higher energy density of the fuel compared to compressed hydrogen gas. Also, the model results could help design better LH2 handling systems for onboard LH2 tanks.
- LH2 analysis like this is necessary to enable effective use of LH2 for delivery.
- The model is a good planning tool, but until it has been validated by data for real-world hydrogen storage and delivery losses, its benefit is limited. The impact has been magnified by making the model available to others.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- It appears this is a final deliverable project, and there is no follow-up work proposed.
- This project was completed, so no future work is necessary.
- The project is ending, so there is minimal future work. It is recommended that the researchers contact users of LH2 beyond the gas companies.

Project strengths:

- A simple thermodynamic model was developed that allowed the team to assess the extent of LH2 boil-off losses; recommendations from the model could help save significant amounts of LH2 in the future. The results from this project have high potential impacts for the implementation of LH2 as a viable fuel.
- The project team is investigating a very important topic for DOE. The team has experience working with LH2, and the project has contacted two major gas companies in its work.
- Overall, this project was very successful in developing a tool to begin to predict hydrogen losses in the distribution chain.

Project weaknesses:

- There are many institutions that use LH2, beyond the gas companies, that the team could have contacted. For example, the project team could have talked with NASA about how to mitigate this challenge. With the amount of hydrogen NASA uses and NASA's strong safety culture, this would have been a very interesting discussion. The team could have also contacted companies that use hydrogen-powered forklifts and are having LH2 delivered. It does not appear that the project team validated the project model.
- While the model is useful and the PI did a good job in simulating different driver usage profiles, more real-world data is necessary to continue the validation of this model. Also, little data on boil-off recovery benefits was obtained.
- The proposal to work on computational fluid dynamics models for modeling top-fill losses might not be that important, given that the extent of the losses from boil-off is limited.

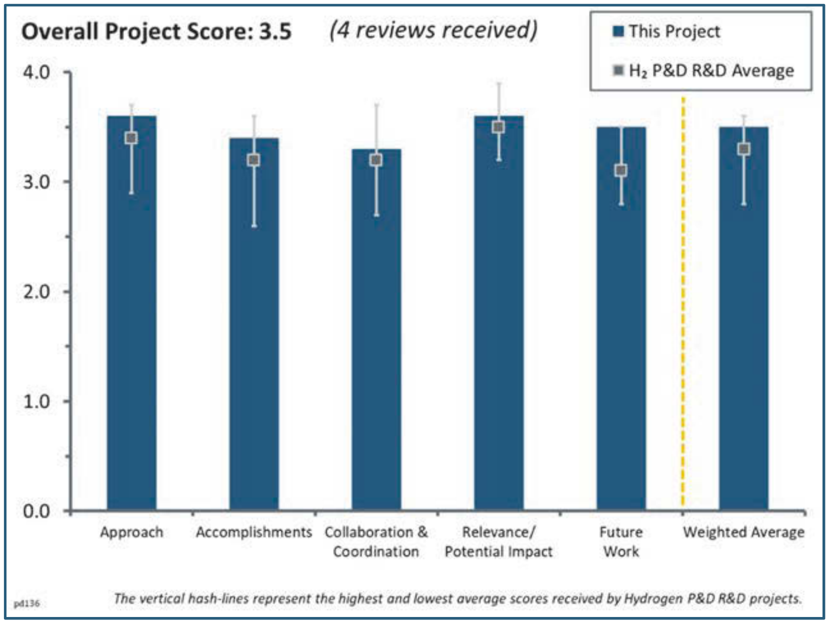
Recommendations for additions/deletions to project scope:

- Possibly there should be follow-up work to instrument delivery trucks and refueling stations to help validate the model over a longer period of time, along with continued refinements in the model to accommodate actual fluid behavior.
- There are no additional suggestions to the project scope.

Project #PD-136: Electrochemical Compression

Monjid Hamdan; Giner ELX, Inc.

Brief Summary of Project:



This project will develop and demonstrate an electrochemical hydrogen compressor (EHC) that is lower in cost, higher in efficiency, and more durable. Specifically, the project will (1) fabricate hydrocarbon membranes with enhanced properties for use in EHCs, (2) improve EHC water and thermal management, (3) optimize stack hardware and demonstrate cell performance, and (4) build a prototype system. Development of reliable and low-cost, high-pressure hydrogen systems is needed to enable market penetration of fuel cell electric vehicles.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project identifies and addresses key issues for electrochemical compressors of water management, thermal management, and mechanical strength. The approach of utilizing hydrocarbon membranes should provide benefits of lower osmotic drag and lower cost. The water management membranes should improve water management and lead to better durability. The project milestones are logically laid out to lead to demonstration of a compressor that meets the project targets.
- The team had a good understanding of the whole system; the team did not focus just on membranes or one specific technical challenge. Focusing on delivered cost, reliability, and performance is essential. The team’s ability to paint a full picture, then focus on low-technology-readiness-level (low-TRL) research, is appreciated.
- The team had a logical approach to addressing major barriers of electrochemical hydrogen compression including advanced membranes, water management, and cell and stack scale-up.
- The project has a sound approach.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The new membrane showed a 30% reduction in electrical energy usage (kilowatt-hours per kilogram of hydrogen) at $1 A/cm^2$, 350 bar. The project has reduced electro-osmotic drag (EOD) by 30% compared to the perfluorosulfonic acid (PFSA) baseline. The project has reduced back diffusion of hydrogen by 50% compared to baseline PFSA. The project has tested cell design and cell components at up to 5000 psi. Energy consumption per kilogram of hydrogen is still far from the target of 1.60 kWh/kg.
- This project is making excellent progress toward Year 1 milestones. The team already achieved the Year 1 go/no-go milestone.
- Successive progress has been made throughout the year, leading to promising results.

- There is good progress according to the plan; however, this project may be behind others developing a similar system. The team has to accelerate progress to be competitive and relevant.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The team has very good collaboration with academia, the national laboratories, and private partners.
- The collaborations between the partners appear to be working effectively.
- The collaborators are clearly listed, along with their roles.
- The team needs better collaboration with end users and operators. Mechanical compression is getting cheaper, quieter, and easier to use, year over year. The team should be sure to set the right targets and be clear about what the right use cases are for this technology; it will help focus development.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Compressors are a major cost for hydrogen refueling stations and are also one of the parts most responsible for station downtime. The electrochemical compressor can potentially address reliability and cost concerns. The proposed work has the potential to reduce cost and improve efficiency of EHCs.
- Electrochemical compression has excellent potential to be the lowest-energy and lowest-cost option for compressing hydrogen to required refueling pressures.
- Alternative compression technologies are of high interest to the industry. A solid-state system has advantages in terms of noise and footprint; there are concerns over how this technology scales. It would be interesting to understand the potential for these cells to scale up to 120+ kg/h at 70 MPa output pressure, which would be relevant for where the industry is going with high-demand regions (e.g., Japan, California, China).
- This project can have enormous impact if scale-up challenges are overcome.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- Plans address critical issues of back diffusion, durability testing, and cell area scale-up.
- Future work is focused on completing membrane studies, scaling up to 300 cm^2 active area, and increasing operating pressure. Further membrane development should reduce back diffusion and increase efficiency.
- It will be interesting to see how the technology scales. Focusing on mechanical integrity of larger cells may be of interest for increasing output of individual stacks.
- Future work clearly addresses the challenges necessary for the project's success.

Project strengths:

- Membrane materials and packaging are clearly the limiting factors to scaling up a viable stack. The team is focusing on the right things.
- The project approach is well defined. Project progress has been promising, and future work is clear.
- The project's hydrocarbon membrane should reduce cost, EOD, and hydrogen back diffusion.
- The project has a strong approach and is making excellent progress.

Project weaknesses:

- The team needs to accelerate fielding viable high-capacity units. Development in parallel on aspects other than membranes could help. For example, structural integrity of larger areas and high-output units is needed. In addition, this project could benefit from collaboration with others in the community; a large part of the issue here is material science. The team could benefit from focusing externally on centers of excellence to accelerate development.
- Aromatic hydrocarbons can be hydrogenated under some conditions, and the high hydrogen pressure and presence of platinum-group-metal catalysts are conditions that make this reaction more likely. It is not clear whether the project has evaluated the membranes to see if this is occurring and what the impact on durability would be. This could be a second degradation mode (in addition to mechanical failure).
- Overlooking the effort required to scale up from 50 cm^2 to 300 cm^2 is a project weakness.

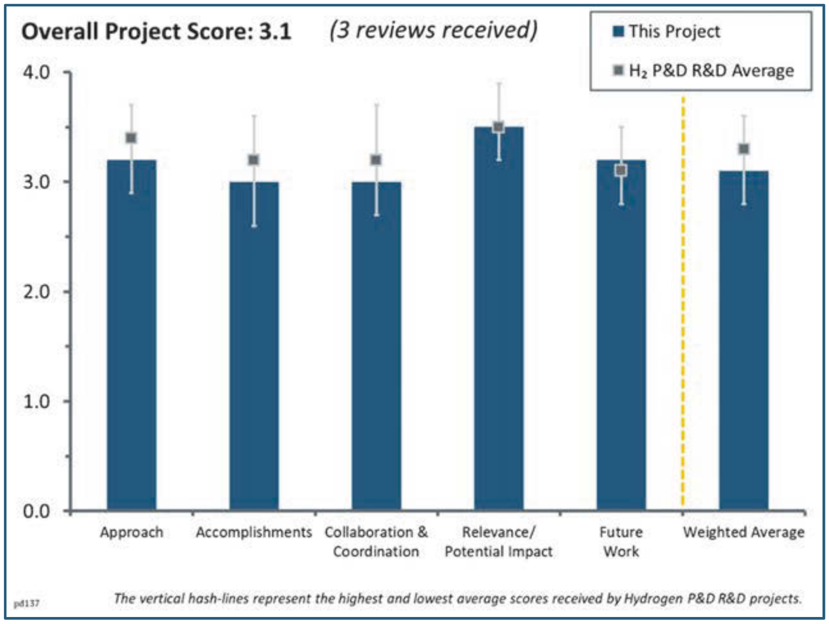
Recommendations for additions/deletions to project scope:

- The team should add pressure cycling testing to the stack test plan, especially for 300 cm^2 stacks.
- The team should look for any evidence of hydrogenation of the aromatic polymer backbone.

Project #PD-137: Hybrid Electrochemical–Metal Hydride Compression

Scott Greenway; Greenway Energy, Inc.

Brief Summary of Project:



There is a need to increase the reliability, reduce the cost, and improve the energy efficiency of gaseous hydrogen compressors. This project seeks to address this challenge by developing a hybrid electrochemical–metal hydride (EC-MH) compressor. The project will analyze and screen potential hybrid compressor systems and materials, conduct experimental tests, develop a hybrid compressor system model, and build a prototype unit.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The overall approach of this work is strong. The methodology addresses most of the conceivable steps for improving the overall technology readiness level (TRL) and directly addresses cost goals and U.S. Department of Energy (DOE) targets. While not part of the scope of work, it would be worthwhile to indicate the likelihood of reducing some of the major costs such as membrane electrode assemblies (MEAs) and metal hydrides, as these are the largest cost drivers and have historically been difficult to lower. As it stands, it appears as if the biggest obstacle to making this technology economically feasible is left unexamined. Currently, the documentation presented listed MEA costs at five times higher than the cost required to meet DOE targets. Likewise, metal hydrides are three to four times higher than the costs required to meet DOE targets. These issues should be addressed, at least in the abstract, as to how the system could be made more cost-effective.
- The project approach combines an existing EHC and MHC.
- The combination of an electrochemical hydrogen compressor (EHC) and a metal hydride compressor (MHC) has potential to increase efficiency using heat from the EHC for the MHC. The work should take into account thermal and mechanical properties of the membranes. Nafion 117 has a glass transition temperature of around 120°C–130°C, which is considerably below the temperatures being considered for the pump operation (up to 170°C). Mechanical properties of the membrane above the glass transition temperature are expected to suffer, and the membrane's durability at these temperatures with a pressure differential across the membrane is suspect. It is not clear that the project gives enough attention to controlling water content in the system and integrating the water control with the rest of the system. The EHC needs to remain well hydrated to operate at the temperatures described, and the EHC will require a pressurized system with high water partial pressures to maintain good conductivity in the Nafion membranes. The metal hydride system requires very low water partial pressures (likely sub-parts-per-million [sub-ppm] to meet durability requirements). The system diagram shows a pressure swing adsorption unit in the design, but it is not clear that the requirements and performance of this pressure swing absorption (PSA) system are integrated with the rest of the system, and the experimental plans for testing PSA systems under the relevant conditions for their hybrid compressor are not described. Water management will be crucial for this design and needs more attention.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- So far, the progress of this work is good. There has been strong development in the experimental stage of the project. Models have performed well and are fairly descriptive of the work that has been accomplished. Some small issues were seemingly not addressed in the presentation (high material costs, thermal durability of some materials, etc.).
- Initial results have led to a down-selection of membrane types and indicated polybenzimidazole (PBI)–phosphoric acid membranes are not a good match, owing to physical properties of the membranes and issues with protecting the system against phosphoric-acid-induced corrosion. Finned heat exchange design appears appropriate for metal hydrides. Experiments indicated Nafion stability at high temperature varied parameters during the test (temperature and pressure) and did not return to initial conditions, so it is not apparent that no performance degradation was shown over the test. Over the first 25 hours, the team indicated a constant voltage, but the temperature was increased from 130°C to 145°C over this time period, which would result in changes in the membrane conductivity from the increased temperature. A temperature increase alone would lead to an increase in conductivity and should result in a lower required voltage for the same current. A complicating factor is any changes in hydration level, which was not sufficiently described. It is not clear what relative humidities or water partial pressures are being used in the experiments or modeling. Nafion conductivity is dependent on the water content.
- Operating Nafion far above the glass transition temperature does not bode well for long-term durability of EHCs.

Question 3: Collaboration and coordination

This project was rated **3.0** for its collaboration and coordination with other institutions.

- These are good collaborations for MHCs.
- Collaborations within the project appear to be operating. Collaborations with those doing metal hydride and MHC work appear to be in place and operating well. The project would benefit from collaborations with the membrane community and those working on polymer electrolyte membrane (PEM) fuel cells, electrolyzers, and EHCs. There does not appear to be any collaboration with PEM membrane suppliers or research groups. Supported and doped PEM membranes would offer some advantages.
- The extent of collaboration seems reasonable, though vague terms are used to describe the frequency of collaboration. Further, the scope of work for some collaborators seems extremely limited, to the point of questioning the value of having multiple groups working on specific aspects. Other groups must be taking the lion's share of the work, although what work they are completing seems undefined. It is often beneficial to incorporate the assignment of labor onto the technical slides in which the work is reported.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The potential impact is high if this project is successful and can increase efficiency and reduce cost of hydrogen compression. Hydrogen compression is one of the major costs associated with hydrogen delivery.
- Low-cost, larger-scale hydrogen compression is needed.
- This work is useful, as it relates to several aspects of the Hydrogen and Fuel Cells Program Multi-Year Research, Development, and Demonstration Plan. The project will potentially advance several areas, although, given the lack of a large-scale model and the potential cost inhibitors, there is the chance that it will not have a large impact in the long run. Existing and planned future work may make this clearer, and the project team should be congratulated on the foresight to plan for these long-term and large-scale issues.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The project's future work is clearly outlined and established, and it seems relevant and feasible to improving the project and accomplishing established goals.
- Future work on the MHC system appears appropriate. While Nafion 117 may be appropriate to prove the concept, durability of Nafion at temperatures >150°C under pressure differentials is suspect because of its low glass transition temperature, especially if membrane thickness is reduced. Work on the EHC system operating at T>150°C should look at supported membranes and alternative membranes with glass transition temperatures higher than Nafion's (one possibility is Nafion doped with inorganic oxides). Water management needs to be given a higher priority in work moving forward, as it is critical to the operation of this system.
- The scale of the prototype demonstration system in Tasks 2.1 and 2.2 should be clearly stated. Durability testing and cycling testing should be included in the plan.

Project strengths:

- The project shows a complete effort, running modeling all the way through experimental tests and scale-up. The results seem promising, and milestones are being completed with seemingly good efficiency. The design of the experiment seems complete, and individual tests all seem to be showing good results, with the end goal directly and completely related to improving the work requested by DOE.
- The concept for a hybrid EC-MH compressor offers some potential advantages and opportunities to improve efficiency.
- This is an interesting hybrid compression approach.

Project weaknesses:

- The economic analysis has some small shortcomings—namely, financial assumptions are buried in the results. For example, the type of economic analysis is unclear. Further, there is limited discussion of whether the required specific material costs are reasonable for future efforts. The extent of collaboration could be better indicated. The authors could give an idea of how a functional, large-scale system will benefit the end-use application. For example, they could explain whether this system would lower compression costs, reduce filling time, etc. and indicate by how much various parameters would affect the end user.
- This hybrid approach requires temperature matching, which requires PEM membranes to be operated outside of their normal operating range, with uncertain long-term durability.
- The project could use assistance in the area of membranes and membrane performance. The project has put too little effort on water management, which is a critical barrier for this concept. The team's effort on water management has to be increased.

Recommendations for additions/deletions to project scope:

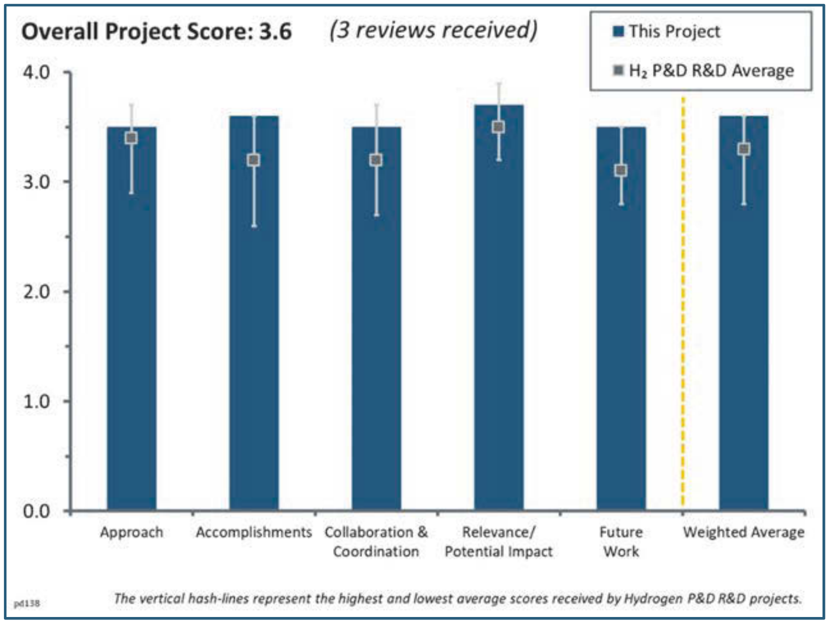
- The team should add durability testing and pressure cycling to the prototype testing protocol. The team should include the breakdown of kilowatt-hours per kilogram for the EHC and MHC systems (based on actual measurements) to allow easier evaluation of progress toward the DOE target.
- It is recommended that the project find a membrane supplier, research group, or PEM electrolyzer/fuel cell system group with which to collaborate.

Project #PD-138: Metal Hydride Compression

Terry Johnson; Sandia National Laboratories

Brief Summary of Project:

The objective of this project is to demonstrate a two-stage metal hydride compressor with a feed pressure of 50–100 bar delivering high-purity hydrogen gas at an outlet pressure of 875 bar or more. The project will identify at least two candidate alloys for both the low-pressure and high-pressure stages, complete a detailed design for the compressor, and build a prototype compressor. The developed technology seeks to address the need for less expensive and more reliable compressors for hydrogen fueling stations.



Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The two-stage metal hydride compressor under development is promising. The design effort was carefully planned, and progress of the overall system integration plan is on track. The system-level focus will allow the team to advance from technology readiness level (TRL) 2 to TRL 5.
- Critical challenges (e.g., thermodynamical properties of metal hydride alloys, overall energy efficiency, system design optimization) have been identified and are addressed in a perfect way.
- This project has a consistent and linear approach: (1) identify materials, (2) check thermal conductivities, (3) verify with a system-level model, (4) design the prototype, and (5) build the prototype.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Accomplishments and progress so far for this project are excellent to outstanding. Scientific and technical challenges have been identified, and excellent progress has been demonstrated. The project has accomplished high-pressure characterization of these alloys, along with development of the world-class instruments needed for this task, and progress is very good. The project is on a very good track. The identification of possible heat pumps to be used to reach the required energy efficiency is an important milestone. Analysis and optimization of the design of the system are excellent.
- The project team met all milestones since the last DOE Hydrogen and Fuel Cells Program Annual Merit Review. Much work seems to have been done in simulation and design.
- There is progress toward most of the objectives of system design and integration targets. The materials selection work is somewhat under-emphasized. It was not clear whether the 20-minute target for the half-cycle proposed is already achieved. In the future, greater clarification of the performance gaps of different aspects of the project, a clearer separation of predictions from modeling, and a discussion of the results achieved so far will be needed. The team's milestone 7.1, currently 50% complete, will be an interesting challenge for the team.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- The team members are very knowledgeable and are close to the "best-in-class" in metal hydrides. Collaboration between Sandia National Laboratories, Oak Ridge National Laboratory (ORNL), and Hawaii Hydrogen Carriers, LLC, seems smooth and fruitful and is a great combination of skills.
- The project shows outstanding internal and external collaboration (especially with project PD-137).
- Leveraging other funded projects, such as PD-137 and PD-171, is mentioned. The team has many more opportunities for collaboration, both inside the organization and with other institutions such as ORNL and Ames Laboratory, to help achieve the targets.

Question 4: Relevance/potential impact

This project was rated **3.7** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is highly innovative and most probably will bring about a breakthrough in high-pressure hydrogen compression technologies. Because of capital investment and maintenance expenses, compressors are the most expensive components in hydrogen fueling infrastructures. If the project is successful, highly reliable compressor technologies with lower maintenance costs and longer lifetimes could be developed. The potential impact of this project is enormous.
- This a very important technology. The progress made will go a long way toward changing the market for compression and energy consumptions using metal hydrides.
- Alternatives to mechanical compressors are needed. Metal hydride compressors appear to be an okay candidate, and this work is very important as a means to settle this question once and for all.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- Project plans clearly build on past progress and are sharply focused on critical barriers to project goals. Project plans are a logical extension of what has been achieved so far and what has to be done before project end.
- Proposed future work is consistent and looks reasonable for achieving successful end-of-project goals.
- Although all necessary elements are there in the planning, it is not clear whether some critical bottlenecks can be removed without some re-planning of the tasks and bringing in experts in alloy selection. Right now, the risk of not achieving the target seems high.

Project strengths:

- The project has a strong engineering connection and has made important progress. The challenges are fundamental in nature in materials performance for the high-pressure alloy and energy targets. Irrespective of the potential challenges, the project will improve the state of the art and can be rebooted in the future if the data and capabilities are maintained in a retrievable format after the end of the proposed performance period.
- This project has a great team with a scope consistently oriented toward demonstration of a continuously operating prototype up to 875 bar. There is a clear path toward the end goal, and there have been great accomplishments thus far.
- This is an outstanding project performed by an outstanding team of highly excellent researchers with outstanding perspectives.

Project weaknesses:

- Project weaknesses are not major. The challenging nature of the concept is the high-pressure stage. The high-pressure stage has greater dependency on materials availability, the maturity level of the materials, and how much of the development can be shaped by the current team. The team needs to make more of an effort to engage experts inside and outside the laboratory for help.
- Metal hydrides rely on waste heat, which is not even available at a station. However, this aspect is not really a project weakness. More publications could be a plus.

Recommendations for additions/deletions to project scope:

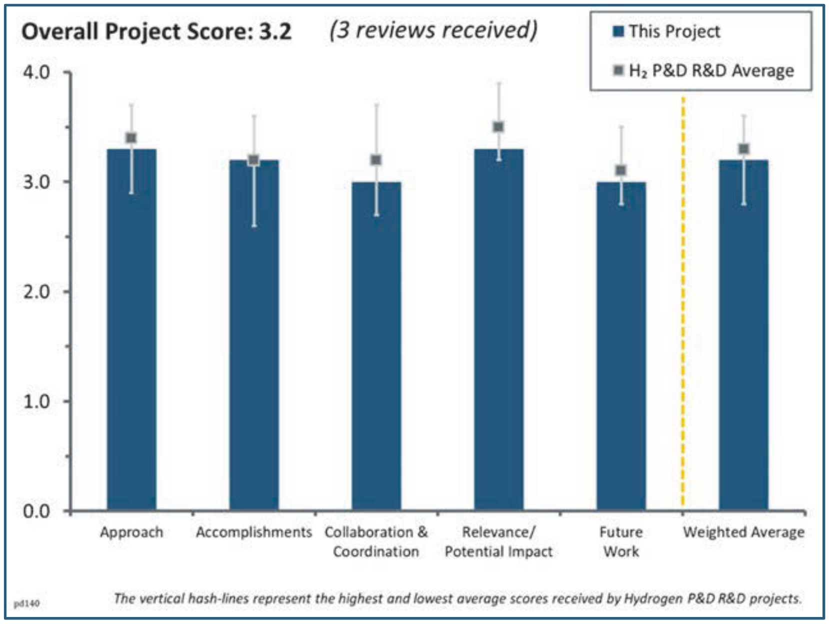
- There are no recommendations for additions/deletions to the project scope.
- Recommendations include more collaborations on the high-pressure alloy phases and a stronger design effort beyond the helical design of the heat exchanger. The nuclear reactor community has lot of experience in this problem. Other parts of the National Nuclear Security Administration/DOE laboratory system can be engaged in support of the heat exchanger design. A good modeling effort might suggest better designs. The fabrication/manufacturing challenge will be less important if performance is not optimal. Overall, the team is aware of the issues and can make course corrections depending on resource availability and the go/no-go points coming up.
- To demonstrate the highest possible energy efficiency, the coupling with the heat pump would be essential. The necessary funding for this should be added to the project.

Project #PD-140: Dispenser Reliability

Michael Peters; National Renewable Energy Laboratory

Brief Summary of Project:

Hydrogen fuel dispensers are a top cause of maintenance events and labor time at hydrogen fueling stations. This project seeks to identify the proper balance between dispenser costs—both capital and operations and maintenance (O&M) costs—and performance. The project consists of three major tasks: (1) a technoeconomic analysis of capital and O&M improvements to the chiller/heat exchanger, (2) reliability testing of dispenser components, and (3) development of an open-source and free hydrogen fueling model.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project tests hydrogen polymer dispenser reliability under real-world conditions by checking for hydrogen leaks and pressure tracking. The project is a field study that can be typecast as a performance approach to safety and reliability. As such, this project has merits.
- The device-under-test (DUT) components are comprehensive. The accelerated testing system, leak detection, and materials testing are very well conceived.
- The approach appears reasonable for the limited costs associated with this task. It would be beneficial if the presentation had more details on the types of failures, such as internal versus external leaks, valve failures, and contamination. Using multiple dispensers allows for maximum tests in a minimum amount of time. Selecting multiple suppliers for DUTs also increases the quality of data.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The accomplishments reflect an impressive effort to set up and establish a detailed experimental design and a state-of-the-art test apparatus. The actual results could prove to be invaluable.
- Good collaboration with manufacturers has resulted in the testing of multiple components. Slide 15 showed that the project infrastructure had been well designed, and slide 18 showed that the project's approach can successfully replicate real-world dispensing conditions. No information was provided on the hydrogen wide area monitor pressure sensor. On slide 13, it was stated that material testing was to be done at Sandia National Laboratories (SNL), but no additional details were given. From the presentation, one could not conclude that the two laboratories interacted on the project. Similarly, the statement that the reliability of components was statistically assessed by researchers at the Colorado School of Mines cannot be assessed; no details were given as to how the statisticians assessed mechanical failure.
- Progress is being made, but it is a little slow. The test set-up has been completed and commissioned, and the dispenser components are now ready for testing. A simple schematic of the dispenser, DUTs, and

recirculation loop together would be beneficial to understand the level of effort put into design and assembly.
- The presenter appeared very convinced and provided data to prove his point. However, the reviewer's knowledge of this technology is limited.

Question 3: Collaboration and coordination

This project was rated **3.0** for its collaboration and coordination with other institutions.

- Industry involvement may be challenging because of the competitive nature of this field. Involvement by refueling station developers might be helpful.
- There is good collaboration with SNL in the area of polymer materials characterization, and baseline samples have been taken.
- The project has good collaboration with Weh Technologies, Inc., and Walther–Praezision. However, non-disclosure agreements need to be set in place properly, or else the data obtained from the project will not be available to the public as the "Management Plan" claims.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project represents a high-quality effort that is crucial to kick-starting the fuel cell electric vehicle market.
- Collaboration with industry and real-world testing conditions can provide data for assessing the reliability of dispensers and dispenser materials.
- The presenter provided a good, convincing picture of this technology.
- The project team should deliver good additional information on device reliability that could be used to help develop better component alternatives. This project relies too much on the results of this specific round of testing. It would be better to include continued investigations on real-world stations and issues that the dispensers are having; this would give the team a more statistically significant sample to investigate. Also, the team should include failure analysis results on real-world dispenser problems.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The project has a great test plan and system design—now it is time to execute it. A national test center for hydrogen refueling technology could be established, based on the body of work and systems. The test apparatus could be productized for use by manufacturers.
- Now that all the preliminary work is complete, the next phase of the project (actual testing) is the most important and should be given time to continue. It looks as though the project is slated to be complete by the end of September, but consideration should be given to the team's continuing testing until multiple failures have occurred and there is enough data to draw conclusions.
- The presenter provided a good, convincing picture of this technology.
- It is not clear what materials analysis will be provided to materials manufacturers (slide 22). It is also not clear that a well-thought-out process is in place for such an analysis.

Project strengths:

- This project identifies the most likely problems with reliability on hydrogen fueling stations (dispensers) and develops a test rig to be able to try to determine failure modes. Overall, the budget is small compared to the potentially positive results that could help minimize station down time.
- The project's scope, test design, and test system are excellent.

- The project's strengths lie in its real-world failure assessment and close collaboration with industry.

Project weaknesses:

- This project has no material weaknesses.
- More details could be given on the types of failures, and some effort should be made to continue monitoring real-world stations for issues as they arise. More details could also be given on the design of the overall test set-up, including schematics.
- A collaboration plan with SNL is lacking. Furthermore, there is no plan for how the project will document failure or what the properties of materials that need to be monitored are.
- The project's weakness is that the devices are not being tested commercially (i.e., outside the laboratory).

Recommendations for additions/deletions to project scope:

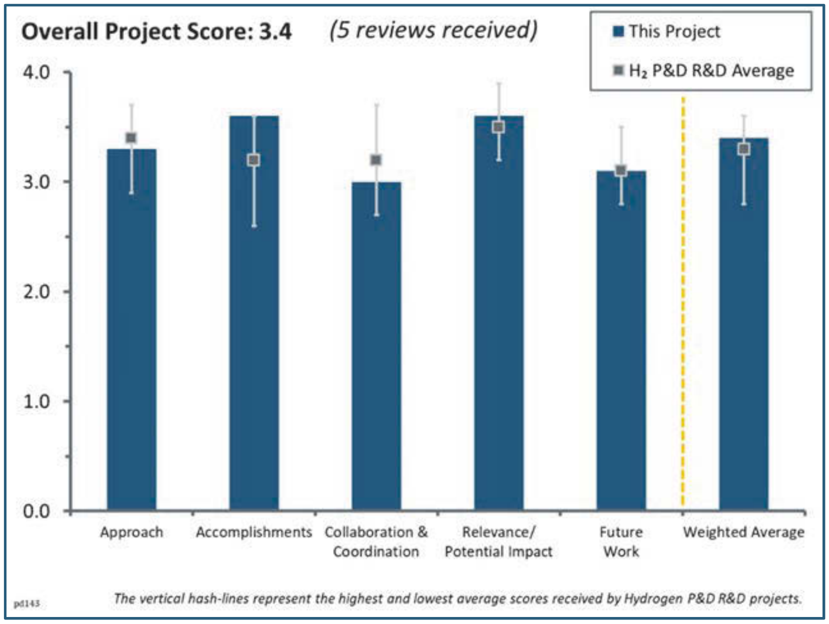
- There are no recommendations—the presenter provided a good convincing picture of this technology.
- Testing of these devices should continue until the planned tests are complete. These data should then be compared to real-world dispenser failure data that should continue to be compiled in a database.
- The project does not seem to have a well-defined plan on future direction. In particular, the project lacks objectives and an approach of how to document failure based on a set of indices/parameters that can be used as measures of reliability and safety. The future work reported on slide 23 is vague and lacks specificity and targets.

Project #PD-143: High-Temperature Alkaline Water Electrolysis

Hui Xu; Giner, Inc.

Brief Summary of Project:

This project aims to develop high-temperature (HT) molten alkaline electrolyzers with improved electrical efficiency and reduced cost. The electrolyzer will operate in the temperature range of 300°C–550°C. Specific project tasks include (1) development of porous ceramic oxide matrices, (2) incorporation of molten hydroxide electrolytes into the porous matrices, (3) selection of anode and cathode catalysts, (4) assembly and testing of single cells, (5) construction and testing of a 1.8 kW electrolyzer stack, and (6) system and economic analysis.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project team is investigating the use of molten hydroxides in porous metal oxides for use in HT alkaline electrolysis. The approach could potentially lower the energy requirements for hydrogen production, improve reaction kinetics, and reduce steady-state voltages. The approach for making the materials is fairly simple and straightforward, which is an inherent advantage for commercialization efforts. The performance of these systems, based on the project data and milestones, is rather good, and the systems have reasonable stability. The authors have addressed some corrosion issues with their cells that were limiting performance (slide 15). The cells "nearly" achieve the metric of <1.50 V at current density of 1.0 A/cm^2 or <1.40 V at 0.6 A/cm^2 (slide 16). This is a fairly impressive performance and very reasonable progress for this effort.
- The overall approach of infiltrating hydroxide into porous alumina and zirconia is good. This project has promising potential for large-scale hydrogen production with a low-cost electrolyte/matrix.
- The project has an interesting approach to benefit from higher operating temperature (faster kinetics, lower catalyst cost).
- The project has a solid foundation and a thorough approach.
- The project appears to use a relatively simple approach. Several metal oxides from Zircar Zirconia, Inc. (Zircar) were tested for compatibility as porous matrix phases for HT alkaline OH- electrolytes. It is unclear whether the technical targets are much of a challenge, aside from achieving 90% lower heating value (LHV) efficiency, which may be claimed based on an energy balance with some generous assumptions. For such a relatively simple scope, more detail would be expected on the individual components. Perhaps significant portions of information are being withheld to protect intellectual property. For instance, the modus operandi is not explicitly identified, which makes it challenging to consider the degradation mechanisms within them.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The authors identified technical targets of (1) composite electrolyte OH- conductivity of >0.1 S/cm, from 300°C–550°C, (2) per-cell area-specific resistance of ≤0.2 ohm-cm^2 from 300°C–550°C with a 200-micron membrane, and (3) stack electrical efficiency of >90% LHV H_2 with a current density of 1.2 A/cm^2. Technical targets 1 and 2 were carried down to the four milestones and go/no-go decision listed on slide 5. Technical target 3 on stack efficiency did not seem to be included in the current milestone set. The authors have achieved all of the milestones listed for this performance period. They have "nearly" achieved the performance target for the go/no-go decision of single cell performance of V <1.50 V at 1.0 A/cm^2, or 1.4 V at 0.5 A/cm^2 (data on slide 16). Hitting the four milestones is excellent progress. Additionally, the team is incredibly close to the technical targets for the go/no-go decision, which is also good-to-excellent progress. In general, the progress toward the defined technical targets and project milestones for the period is excellent. It is assumed that the technical target of stack electrical efficiency >90% LHV H_2 with a current density of 1.2 A/cm^2 will be addressed in later years for the project, but there were no details about this in the slide deck or verbal presentation.
- This project has outstanding progress in the conductivity increase of the matrix and the reduction of cell voltage and resistance, especially considering the challenges of operating at higher temperatures.
- The project has made very good progress in making the electrolyte matrix and testing of cells. Progress in cell performance over a fairly short period is very impressive.
- There is good progress to date, good responses to review comments, and good mass/energy balance. The team's progress toward project and DOE goals is substantial.
- The presentation mentioned 100% progress for Tasks 1–4, but there was no meaningful discussion of the catalyst development in the presentation, only a mention that the catalysts were optimized. There was no discernable discussion of the percent increase in activity/corresponding decrease in polarizations associated specifically with the hydrogen evolution reaction and oxidation evolution reaction catalyst. Overall, minimal concrete detail was given on progress.

Question 3: Collaboration and coordination

This project was rated **3.0** for its collaboration and coordination with other institutions.

- The authors list the University of Connecticut (UConn) as a collaborator for fundamental studies of matrix coarsening and corrosion. This data is illustrated on slide 17. From the supplementary slides, it seems that the team has added UConn to address previous review comments regarding the stability of these electrocatalysts at higher temperatures. The project team has taken a good step toward addressing previous reviewer comments. The results with UConn seem aimed at addressing issues with the current collectors. UConn's role on this project seems small, but the authors are making progress and hitting their milestones. Additional collaboration would make sense only to address knowledge/skills/capability gaps on the team.
- The project has excellent collaboration with the UConn and Giner ELX.
- It appears as if collaboration has been limited, or at least, the presentation communicates that collaboration has been limited.
- Giner ELX is collaborating with P. Singh's group at UConn. It appears that slides 17–18 are based on UConn work. It would be advisable to leverage the UConn team's skills more fully; it is unclear whether the matrix solubility study was planned for MO-3 only. It is also unclear what is unexpected regarding the corrosion determined by the metal stability tests. Energy balances with Giner ELX are not necessarily collaborative efforts since there is a pre-existing link.
- UConn seems to be the only collaborator. Energy Materials Network nodes should be engaged for independent evaluation.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is making good progress toward its technical goals, which will help enable the large-scale deployment of hydrogen for energy applications. The project is relevant and impactful to the H2@Scale concept. The performance of the materials is reasonable and is hitting the technical targets associated with the go/no-go decision, which also makes it relevant and impactful to H2@Scale.
- Although the efficiency may be lower, this approach has the potential to make large-scale electrolyzers meet the DOE's targets. The cost of hydrogen is a concern with the high operating voltage and the corresponding energy requirement.
- This work has the potential to reduce the capital and operating cost of water electrolyzers.
- The project consists of very relevant work. The true quantitative assessment of corrosion is uncertain. If corrosion is truly a minor issue, this work seems very promising.
- This alternative electrolyte route to steam electrolysis could have a noticeable impact if the cost models are reliable. However, it is unclear that assumptions such as "90% heat recovery in the heat exchangers" are feasible.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The work seems to focus on performance increase. Because targets seem to be mostly met, some effort may shift to durability/corrosion. It seems that a thinner electrolyte may not be absolutely necessary; rather, a stable system at current performance levels may be sufficient to move forward. Performance could then be improved at a future time, once long-term durability issues are fully sorted out.
- The project team's future plans focus mostly on additional optimization and fine-tuning of the current approach. This is a reasonable path forward since the system seems to be meeting performance targets. In general, the slide on future plans (slide 23) does not include much detail on what will be done. There are no technical targets, alternate paths, barriers, or timelines presented on the slide to make it easier to assess the team's path forward.
- The future plans consist of addressing major challenges of stability associated with this class of materials.
- The future work is not very specific. It is unclear how matrix stability will be addressed. It seems that only three matrix oxides, supplied by Zircar, are in consideration, so it is unclear whether there are any custom formulations being considered with compositional or morphological changes. It is unclear whether the ternary electrolytes are expected to improve both conductivity and matrix/metal stability or if they will likely exacerbate the corrosion challenges. The plans for addressing the expected sealing challenges are not communicated.
- Corrosion mitigation of stainless steel is a concern, and the mitigation plan was not clearly defined.

Project strengths:

- This is a unique approach to hydrogen production that offers opportunities for lowering the energy requirements of hydrogen production. The methods for making the materials for this system are simple and straightforward, which will be beneficial for commercialization efforts. The authors are hitting all of their technical targets and milestones.
- The project leverages existing paradigms (OH- electrolyte solutions, HT operation of oxide-type cells, materials available from a commercial powder supplier) to demonstrate an alternative alkaline electrolyzer technology.
- The project has a novel approach that promises lower capital and operating costs, compared to polymer electrolyte membrane water electrolysis (PEMWE). This promises stability data at a 30-hour level at a good current density (600 mA/cm^2).

- The project has shown very good performance, and the team has a good approach for a potentially practical system.
- This is a good team with good progress.

Project weaknesses:

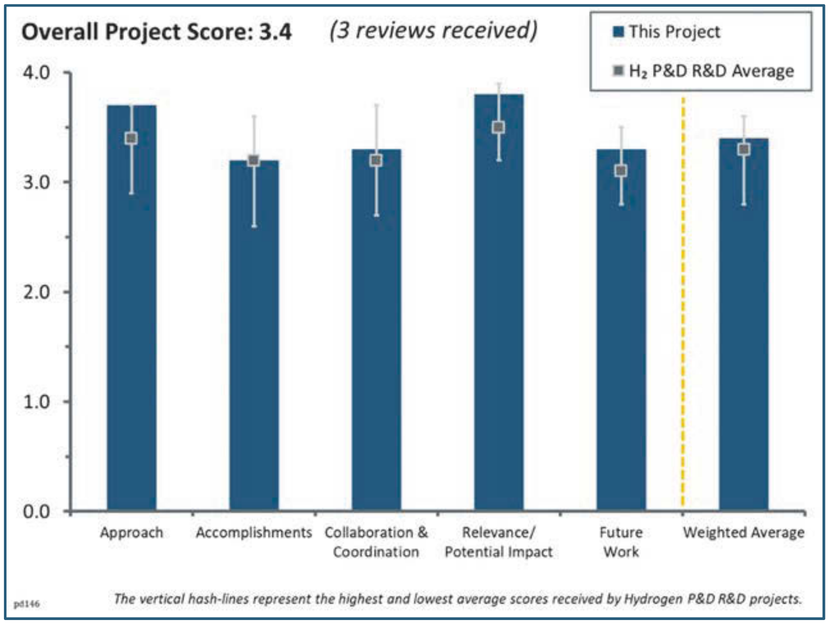
- The project does not involve much external collaboration. The current collaborator, UConn, has a relatively small role in the work. It is not clear whether the team needs additional help from external parties. The future plans and challenges were not very detailed, which made assessing the next year of work difficult. The energy and cost balance were a bit confusing on the slides and during the oral presentation. The comparison between HT alkaline electrolysis and PEMWE was difficult to follow. The assumptions and comparisons were not obvious. The project could be improved with a bit more consideration in detailing the cost/energy balance aspects of the work.
- The project does not share much detail on the methodologies and phenomena utilized, or what specifically is being targeted by the approach to improve the active components. This gives the impression that the electrolyte and matrix formulations are being explored by a relatively unambitious mix-and-match approach. This approach may yield some demonstrable progress in the technology, but it is unlikely to provide any breakthroughs.
- The local temperature of cells needs to be measured to avoid overestimating the cell performance from local temperature increases in the exothermic mode of operation.
- Longer-term testing is required to assess material stability.
- It seems as though collaborators were underutilized.

Recommendations for additions/deletions to project scope:

- The project could provide a more detailed cost/energy balance to better identify how this approach compares to more traditional technologies, such as PEMWE.
- It would be advantageous to include more analysis of the root cause of metal and matrix corrosion so it can be addressed.
- It is critical to address corrosion of stainless steel bipolar plates and inactive metal components.
- It may be wise to prioritize durability over performance; at present, performance seems adequate, and durability seems good.
- The project team should initiate long-term testing of the matrix and cell to gain a better understanding of material stability.

Project #PD-146: Advancing Hydrogen Dispenser Technology by Using Innovative Intelligent Networks

Darryl Pollica; Ivys Inc.



Brief Summary of Project:

The primary objective of this project is to develop a robust and cost-effective system for dispensing and measuring hydrogen; the system is meant to further enable widespread commercialization of fuel cell electric vehicle (FCEV) technology. Key project activities include (1) development of robust sensor hardware and algorithms that improve accuracy based on empirical testing and enhanced meter temperature measurement; (2) development, testing, and demonstration of the use of dedicated short-range communications (DSRC) for use in vehicle refueling; and (3) simplification and cost reduction of flow control and hydrogen pre-cooling systems.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project team is focused on critical dispensing issues: safety, accuracy, and cost. The project has a great set of collaborators to accomplish the objectives.
- The approach is comprehensive and well-focused.
- The approach is sound, although the description lacks detail. From the presentation alone, it is somewhat unclear how all of the equipment interacts and fits within the scope. For example, on the slide titled "Approach (4)," the Coriolis meter is not shown in the diagram, yet it appears in the slide titled "Approach (3)"; it is clearly a key part of the system.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The accomplishments achieved so far are good. The Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) target for accuracy has already been achieved. It appears further progress is required to lower the total cost of the system to meet future MYRDDP targets. Several mentions of no-cost extensions are present, and the project schedule should be maintained.
- The project team's accomplishments are impressive.
- The principal investigator (PI) provided a good, convincing picture of this technology.
- This project is a year behind schedule and will likely need even more time beyond that. There is great progress on improving dispenser accuracy, although more information should be provided on (1) potential challenges (e.g., reliability and long-term accuracy under real station versus laboratory conditions), (2) how the team will assess the robustness of the design to those challenges (preferably beyond long-term field

testing), and (3) contingency plans. The presentation was completely silent on progress toward the cost-reduction objective. Although interaction with an automotive original equipment manufacturer (OEM) was identified in the summary, this critical aspect was not addressed in the plan.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- There was a sufficient number of agencies and private companies listed in the collaboration and coordination section of this presentation.
- This project has an appropriate and qualified set of partners. The team has demonstrated collaboration with a Coriolis meter company, but strong interactions with other partners have not yet been demonstrated. This is primarily because project activity seems to be concentrated toward the end of the project, and the project has been delayed. It is suggested that the team engage the National Renewable Energy Laboratory and Air Liquide to learn about known challenges to station reliability, thereby minimizing surprises during site demonstration.
- The project has strong collaborators with excellent backgrounds in this field. An important aspect that is not made clear includes how frequently the collaborators met, shared data, or ran experiments for other team members. It does appear that future collaborations will be frequent in Phase 2.
- FCEV refueling station developers and vehicle/part OEMs should be included as advisors to gain market insight and improve the team’s understanding of metering technology.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is directly relevant to the MYRDDP goals. Project improvement has the potential to advance infrastructure goals.
- The results of this effort will be critical to the future success of the FCEV refueling market.
- Achieving accurate and reliable hydrogen dispensing at a reasonable cost is critical to the success of hydrogen refueling stations. Unfortunately, the cost axis was not addressed in this presentation.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The development of a plan for improved low-cost manufacturing could be included in future work.
- The future work seems appropriate for this project. However, no work is suggested for planning on the addition of proper receivers to OEM vehicles. It appears that the PI expects OEM manufacturers to put the appropriate technology onboard vehicles in the future, though it is advisable to research and support this assumption.
- The plan for validating the dispensing equipment is good, but it appears the team underestimates the timing of the field testing phase or will not be able to do it justice because of its being cut short. It is strongly suggested that, if faced with this choice, the team seek to extend the project for adequate testing time rather than leave the demonstration partially finished. Several aspects are missing from the plan, including automotive OEM engagement and plans for how to close any shortfall in meeting the cost target.

Project strengths:

- The project seems well-laid-out. Excellent collaborators have been arranged for the project, and the proposed changes directly address the MYRDDP. The proposed technology changes take into account both cost and security.

- This project addresses a critical need. The project has an innovative approach, a good plan to demonstrate the technology, and a good collaboration team.
- The relevance, approach, accomplishments, and presentation of this project are all excellent.

Project weaknesses:

- The PI indicated that the addition of DSRC technology would lower costs, but no cost data was provided. Even a simple technoeconomic analysis would be beneficial. There is a given assumption that the vehicle manufacturers will include the proper technology in new vehicles. Should that not be the case, this technology will be rendered somewhat useless. The presentation indicated that no-cost extensions have been granted, perhaps more than once. This could indicate potential schedule problems.
- There is no OEM engagement. The technology will be useless if not adopted by the OEMs. It seems the team has not yet addressed the cost objective (based on information provided). There is an apparent presumption that Coriolis technology is sufficiently robust to work in real station environments for a reasonable lifetime (many years).
- The engagement of vehicle OEMs and refueling station developers could be helpful.

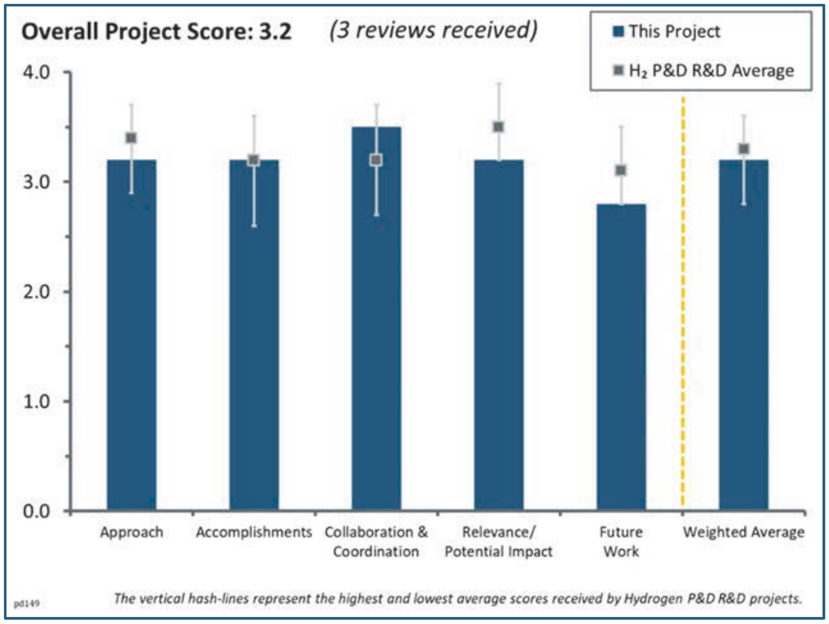
Recommendations for additions/deletions to project scope:

- No changes to the project scope are recommended.
- The presenter provided a good convincing picture of this technology.
- DOE should look for ways to take advantage of the improved dispenser accuracy before the proposed communications standard is adopted.

Project #PD-149: Hydrogen Dispensing Hose

Jennifer Lalli; NanoSonic, Inc.

Brief Summary of Project:



This project aims to develop a hydrogen hose for fuel cell electric vehicles (FCEVs) that is (1) engineered to be flexible and enable hydrogen delivery at less than \$2/gge, (2) durable in conditions of roughly -50°C and 875 bar for H70 (70 MPa) service, and (3) reliable and safe for conducting approximately 70 fills per day for more than two years. NanoSonic, Inc., is partnering with two national laboratories, a standards development organization, a local government, and industry to implement and test a cost-effective, metal-free, high-pressure hydrogen hose design that meets the above criteria, resists hydrogen embrittlement and contaminant leaching, and endures mechanical fatigue.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project, scope, focus, approach, and accomplishments are all excellent.
- The approach used for the work, performed from the third quarter of fiscal year (FY) 2017 through the second quarter of FY 2018, was well-thought-out. Many issues were considered thoughtfully, such as relevant performance properties of the produced hoses, partnerships that leverage expertise to fill knowledge gaps, and expectations on performance needed to get to the next stage. It is possible that some detailed modeling and analysis of the pressurized hose-fitting combination would have predicted the issues related to the fitting (i.e., slipping and lack of connection that would necessitate crimping). In hindsight, it appears that the fitting aspect presents a barrier that may prevent project success. Increased rigor on the analysis side might have enabled addressing this sooner.
- Goals were established to meet H70 pressure requirements (for burst and durability) and achieve low cost. Testing was not aligned to evaluate whether the hose will actually meet the needed pressure. Thus far, the failure has been at the fittings, but this failure has precluded determination of whether the composite hoses are feasible. It is concerning that there is an advancement of production capability prior to there being any proof that the hose can meet H70 burst requirements. It is unclear from the presentation whether the composite hose is compatible with the fittings. There was not a clear path forward as to how this severe challenge with the fittings is going to be overcome. The motivation for moving away from the current hose configuration was not clearly stated. Also, if hydrogen embrittlement of the metals in the current hoses is the issue, it is not clear that the current solution to use metal fittings will fully address the issue.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project achieved the following critical criteria:
  - 3500 bar hydrostatic burst strength (>50,763 psi) held for one minute
  - 875 bar pressure cycle at (50,000x at -50°F and 50,000x at 85°F)
  - No contaminant leaching, competitive cost, mechanical durability, and environmental lifetime
- Progress has clearly been made. Pressure testing has been used to identify a failure mode not anticipated (i.e., slippage of fittings) and to quantify the pressure loads at which this failure occurs. Cardinal Rubber & Seal, Inc. (Cardinal) developed a very good engineering solution to bypass this failure mode. The principal investigator (PI) and her team have also identified supplemental activities (e.g., digital image correlation [DIC] and dynamic mechanical analysis [DMA] time–temperature super-positioning [TTS]) that provide insight on component performance through leveraged use of laboratory capabilities. Clearly, more testing is needed to determine whether this engineered solution is durable and enables the hose to reach the desirable maximum pressure limit.
- It is clear that work has been done, but the best results reach only 60% of the required goals. Thus far, the progress would not justify continued investment in the next steps of production and testing. Prior to further investment in this technology, there needs to be data showing the feasibility of the hose's being able to handle the operating loads.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- The PI has engaged and added partnerships such that all those involved provide meaningful and substantial contributions to the development of this technology. These contributions are designed to leverage appropriate capabilities of each partner, thereby making effective use of the partnership itself.
- The project could involve FCEV station developers.
- The company has several collaborations and is reaching out to involve local suppliers and eventual customers, but it is not clear in all cases that these collaborations address the most pressing issue of meeting baseline burst pressure requirements. It is not clear how the Cardinal testing is relevant, as there is an inherent limitation on the company's testing capabilities; the testing is well below the pressures needed for the application.

Question 4: Relevance/potential impact

This project was rated **3.2** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Obviously, the results of this effort are critical to the commercial success of the FCEV refueling market.
- This effort has significant relevance to improving durability and lowering the component costs associated with fueling infrastructure. The project stands as an exemplar on how material properties and material interfaces can limit performance and proposes a scope of work to investigate these limitations (even though it may not have intended to do so).
- This project seems more like company-specific product development outside of the scope of the current research and development program. There are existing products that meet this requirement. It is not clear (1) that this technology provides a better solution, (2) that the lack of this product will inhibit the application of this hydrogen technology, and/or (3) that this approach will even be successful.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed future work is very important.
- The proposed future work of DIC for multi-strain imaging may provide insights on failure modes and mechanisms that occur at the fitting–hose interface. The DMA TTS work proposed will also provide some information regarding long-term testing and the durability of the component under abnormal handling conditions. That said, it is not clear to what degree that further burst pressure testing will be used and when it will occur. Perhaps that testing depends on the outcome of the DIC analysis. More clarity on the path forward—and what that timeline is now changed to—is warranted.
- The primary issue of not even coming close to meeting the H70 burst pressure requirement was not clearly recognized. There was no clear path forward for how this deficiency will be addressed.

Project strengths:

- The well-defined goal and the approach are project strengths. The project has outstanding partnerships that leverage each contributor's expertise and capabilities to achieve progress and further insight on hose performance. Given reliability issues that face the infrastructure industry, this effort should have a large impact once a final hose design and manufacturing method are established.
- Project strengths include good collaboration in the development process, good facilities, clear goals, and abundant data generation.
- The project plan, execution, and diligence in addressing challenges are impressive.

Project weaknesses:

- The project could have uncovered some of the critical issues related to fitting–hose interface behavior through inclusion of modeling and analysis of the manufactured system. It is not clear that this modeling and analysis was done. Also, the presentation did not provide backup materials, reviewer-only slides, or a data management plan. Finally, given the obstacles uncovered this year, the path forward and schedule are not sufficiently detailed to address how to get back to the original plan of high-pressure testing (or to address whether the project needs to do so).
- The project team did not clearly communicate the issues with the current technology and the unique engineering gap that this product will fill. The work has yet to come close to demonstrating whether the hose is even feasible; there is no clear path forward for how the fittings issues will be addressed. Many different parallel paths are being evaluated, and it was not clear which is the critical path and whether there are decision point criteria for continuation with each. Many technical issues remain unresolved:
  - Whether the metal fittings, which might still be used, are candidates for hydrogen embrittlement—or whether this has even been evaluated
  - How much costs will increase because of all of the modifications of the fitting process
  - What the plan to stop the slippage is
  - Whether the slippage is simply the result of the inherent differences in the composite hose and the fitting materials, and if so, whether this would preclude the achievement of the required pressures
  - Whether there is an alternate path for evaluating the hose's efficacy, thereby justifying all of the effort on the fitting modification
  - Whether there is a known quality control process for coupling these fittings to a composite hose, if/when an acceptable fitting is found
  - Whether there is any consideration of external degradation of the composite due to atmospheric environmental exposure (e.g., salt, ultra-violet radiation, etc.)
  - Whether relevant hydrogen-based degradation mechanisms of the composite are known, or whether tests have been performed

Recommendations for additions/deletions to project scope:

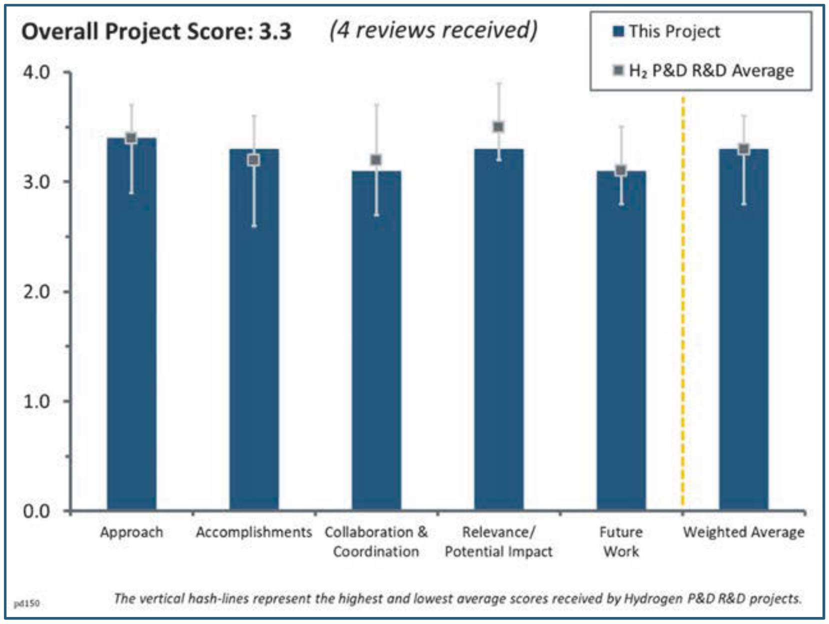
- Modeling and analysis of the manufactured system to uncover some of the critical issues related to the fitting–hose interface behavior could still be added to gain further understanding of anticipated DIC results. Also, modeling and analysis might predict further issues should the fitting–hose interface issue be resolved.
- The project should put a primary focus on demonstrating product feasibility and limit the scaling up of production capability until the product can demonstrate feasibility.

Project #PD-150: Coatings for Compressor Seals

Shannan O'Shaughnessy; GVD Corporation

Brief Summary of Project:

Seal failure is a major contributor to hydrogen compressor maintenance, adding significant downtime and cost to compressor operation. The goal of this project is to improve seal life in hydrogen compressor systems by three to five times. The work focuses on two different types of coatings. For static seals, the project will develop barrier coatings that mitigate hydrogen ingress into the seals, which prevents premature failure. For dynamic seals, low-friction coatings that reduce wear and extend seal life will be developed. A room-temperature polymer vapor deposition process will be utilized to produce thin polymer coatings for both types of seals.



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project has a sound approach to address a critical barrier that affects hydrogen compression, storage, and dispensing reliability. The methodology is both sound and well-thought-out, and it uses a mixture of insightful scientific investigation with clever engineered technology to understand and qualify the effectiveness of the barrier coating solution.
- This project contains promising material for reducing maintenance and cost.
- The issues with the current state of the art and the goals of the current work were established. Reasonable approaches were presented for both lubrication and barrier coatings to inhibit hydrogen permeation. The evaluation approach was reasonable; however, it could be improved by evaluation of the permeation *after* pressurization loading. There is some concern about the durability of a 2-micron-thick polymer/inorganic barrier coating in maintaining its function after pressurization and/or wear loading.
- The project team addresses the challenges with hydrogen material interaction as a barrier and assumes improved sealing treatments as the solution. However, the material has not yet been tested in hydrogen, and there are many assumptions related to hydrogen's and helium's being similar, based on the size of the gas. In fact, solubility has a significant role, and the two are completely different.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project is developing promising materials for lowering maintenance needs.
- The project team has made good progress on performing coatings with the material. The material still needs to be hydrogen-tested. The barrier material needs to undergo pressure cycling, or at least a rapid decompression test after a 24-hour hydrogen soak test, to determine if there is any blistering or delamination of the coating. The coatings on the compressor seals are a good idea, but there has not been

enough work on the durability. The work at Powertech looks promising, but there is no characterization discussed based on the number of cycles endured or whether there was a transfer film on the mating surface. More durability testing on the coating is suggested. It would be good to determine the wear rate, and what impact the mating surface characteristics have on that wear rate.

- The project team has made good progress in making the materials efficiently. The project itself consists of good initial data, although the assumption of helium's being a conservative proxy for hydrogen is questionable. Hydrogen will likely have a higher diffusivity, which would be a relevant parameter. There was no significant reduction in permeability, even without possible mechanical-loading-induced defects. The team has produced excellent lubrication results.
- The project team has made substantial progress in characterizing the morphology, properties, and behavior of barrier coatings to prevent wear and hydrogen degradation. Further analysis in still warranted, such as the examination of the effect of contaminants/particulates on coating stability and the economic cost of the coating relative to system setup and other capital costs.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The project's collaborators have well-defined scopes of contribution that complement one another. These contributions leverage skills, expertise, and capabilities at each institution to gain further clarity on the robustness of this particular technology solution.
- This project has a solid group of collaborators.
- A fair number of references were provided.
- There was discussion of working with other partners such as PowerTech, but the contribution of partners was not obvious during the presentation. It was thought that GVD Corporation was doing the helium permeation testing, but it was Green, Tweed & Co., based on the collaboration table. The collaboration slide was the best at explaining this. Oak Ridge National Laboratory (ORNL) has good hydrogen permeability capability and experience that could be shared with GVD Corporation; it was not clear that this body of knowledge at ORNL was being leveraged.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project has good relevance to technology barriers and presents a method to significantly enhance the reliability of fueling technology. The project also does a good job of anticipating potential issues with the proposed solution and shaping activities to pre-emptively address them.
- The project is relevant and could have a great impact and provide solutions to some current problems.
- The project aims to reduce the cost of maintenance.
- The project team address an important topic that is a cost-efficiency limiting problem. The impact will be more rigorous once the behavior after loading is known. The benefit of the initial coating was very modest. It seems as though this could be improved by additional layers, etc. This type of work could have a broader impact in other areas.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The project is definitely ready to progress to hydrogen, as the presenter discussed, and the compressor testing is the right next step.
- The proposed future work appropriately addresses remaining knowledge gaps and anticipated modes of failure.
- Good short-term and long-term plans were provided.

- The project team could have challenges in meeting the 10-fold reduction in hydrogen permeability, based on initial results; this should really be tested after the system has been mechanically loaded. This work should include some study/characterization of the mechanical degradation of the coating.

Project strengths:

- The project is very clear on goals, approach, accomplishments/results, and roles of partners. Technology development demonstrates a good initial effort toward commercialization. The project has a reasonable data management plan, and technical details are well presented. The team has foresight on potential issues with the proposed solution and has planned actions to mitigate these issues.
- The project consists of an interesting and innovative technology that shows promise in coating, even in tight crevices. The lubrication results are excellent. The development of both an efficient process and a proper testing apparatus are strengths of this project. This technology has the potential for wide applicability and has a targeted insertion point.
- The project has some real value in addressing gas diffusion into materials and wear issues in compressors.
- This project is pretty good.

Project weaknesses:

- Permeation has not yet been evaluated under realistic conditions. Specifically, the effect of mechanically induced damage on such a small-scale polymer/inorganic coating system will be critical—yet the compatibility of the polytetrafluoroethylene (PTFE) and the polymer/inorganic with the hydrogen is not addressed. The project team has not stated whether there will be expected degradation and, if so, over what timeframe. There are also several technical concerns:
    - The team has not discussed whether there is a compatibility issue with these coatings possibly contaminating the hydrogen if they wear off.
    - It would be useful to compare this coating to competing technologies for permeation barriers.
    - It is unclear how the team plans to verify the uniformity of the coating. Also, little was mentioned on the application-induced defects of the coating—this seems like it could be critically important. It is unclear whether there are standard quality assurance practices for this and how this could impact the cost.
    - Perhaps the team could correlate the 20% increase in cost with a percentage increase in lifetime, thus making a business case that this product would be worthwhile.
    - The project team should also clarify whether there is a temperature issue with the durability and the performance of the coatings.
- The team should continue to address durability issues, especially with the barrier coatings on the seals. Rapid decompression after long-term soaks is a good test of whether the barrier is defect-free and the durability of the coating still stands. The wear rate and mating surface influence should be addressed. There are tribology standards, such as pin-on-rotating-disc or reciprocating pin-on-disc, that could be utilized for wear testing. Different sliding surface roughness could influence the wear rate; it is not uncommon for transfer films to build on the mating surface that provides low friction and wear. This should account for mass loss. If not, the mass would be lost as a particulate, which would not be beneficial to the particulate levels in the hydrogen.
- The only real weakness is the lack of detail on the cost of barrier coatings relative to capital costs. Some knowledge is obviously there, but the details are omitted. Also, clarity is needed on total permeability reduction for hydrogen exposure. This was not always clear in the presentation.
- The results have limited applications.

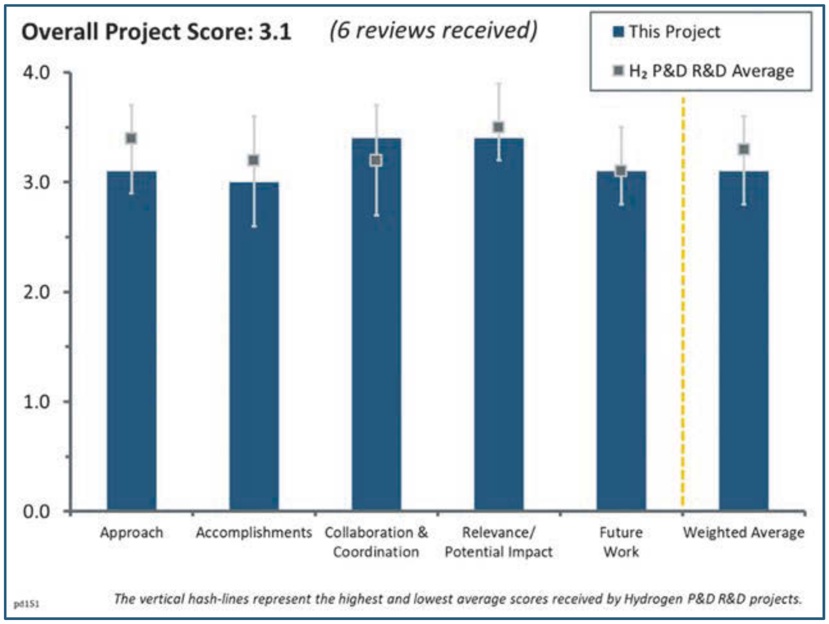
Recommendations for additions/deletions to project scope:

- No scope changes are needed.
- It is strongly recommended that the coatings be evaluated after mechanical loading.
- It is recommended that the team add surface roughness characterization on the mating sliding surface.

Project #PD-151: New Approaches to Improved Polymer Electrolyte Membrane Electrolyzer Ion-Exchange Membranes

Earl Wagener; Tetramer Technologies, LLC

Brief Summary of Project:



The project seeks to develop improved polymer electrolyte membrane (PEM) electrolyzers that will minimize physical and chemical degradation and enable the cost-effective production of hydrogen, enhancing grid stabilization and facilitating remote renewable energy storage. Tetramer Technologies, LLC (Tetramer) will optimize ionomer molecular architecture and membrane configuration with a goal of developing a membrane material superior to Nafion in terms of performance, durability, and cost. A final, down-selected polymer material will be scaled up. The project team is partnering with Proton OnSite, which is providing insight on membrane requirements and testing membrane materials.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This approach seemed reasonable for a Small Business Innovation Research (SBIR) project for developing an optimized ionomer. The project team worked on proving the feasibility of the ionomer process in Phase I before moving to making dozens of ionomers for testing in Phase IIA, at which point the project exceeded expectations and thus received Phase IIB funds to scale materials for prototyping an electrolyzer with Proton Onsite.
- The project team approach seems reasonable. Proton Onsite is a solid partner to direct this work. More information on the design iteration process and how the team approaches the next iteration for this project is desirable.
- The project has a very good approach that combines an appropriate backbone and conductivity along with durability.
- This novel approach has promise to significantly reduce cost.
- The authors are designing conductive polymer architectures for the ionomers/membranes in an electrolyzer. The polymer design, synthesis, and execution are very interesting. The authors do not provide any technical targets (for the polymers or the integrated cell) or milestones on the project. This makes it difficult to evaluate the approach fully because it is not obvious what targets the authors are aiming for, nor how their approach may or may not get them there.
- The project team does show some improved performance relative to Nafion (slide 6), improved swell control (slides 8 and 9), and improved down-selected membranes (slide 13); however, these are mostly relative targets that evaluate the system relative to Nafion or that highlight a net improvement relative to one of the project's own polymers. It would be useful to see absolute performance targets for the polymers and/or integrated cells. While the project team aims to improve the durability and efficiency of low-temperature water electrolysis cells/stacks, the presentation did not include specific goals in those areas. Showing voltage–current (V-I) curves without providing an example of how the improvements will affect

the efficiency and cost of Proton Onsite's 250 kW stack, for example, is concerning. Goals listed on slide 4 include "Work closely with Proton [Onsite]," which is a really good thing, but then "build a prototype [and] assess performance…in customer trials" will not happen with Proton Onsite. It is possible that Proton Onsite will want to see tens of thousands of hours of benchtop operation/performance before any stack ends up in a commercial (i.e., customer) system. The project team should work more closely with Proton Onsite and ask Proton Onsite to provide guidance on how to develop a plan to systematically achieve the project goals.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- A new polymer that appears to exceed the performance of current membranes is a very promising development.
- It is always impressive to see an SBIR project progress the way this one has, from Phase I to Phase IIA, and now to Phase IIB.
- This aspect of the project is difficult to assess because the authors have not provided technical targets, milestones, or go/no-go decisions. The data within the presentation shows performance relative to Nafion or performance relative to other polymers in this study. The authors need to define some absolute technical targets for their polymers and cells. It would also be helpful to see some targets for costs and performance lifetime. The authors do make reasonable progress on the development of these materials. Slide 6 does show improvement relative to Nafion. The improvements in swelling (slides 8 and 9) and durability (slide 7) and the results on conditioning (slide 10) are noted as examples of progress on this project.
- The polarization curves help show the relative improvement over other candidate materials, but absolute targets would help explain how this work would improve over the state of the art. With Proton Onsite as a partner, this data should be easy to show next year. Slide 6 shows the polarization curve for Tetramer Series A (3 mil), which seems to be highlighted on slide 7 showing the 1000-hour durability run. On slide 6, the voltage of this cell at ~1.85 A/cm^2 seems to be around 1.8 V, while slide 7 shows the cell performance closer to 2.05 V. The reason for the apparent disparity is unclear.
- The project results have shown promising durability at 1000 hours. Hydrogen crossover needs to be further reduced. A cost analysis is mentioned, but no results are reported in the presentation. Little or no progress was made compared to the Phase IIB baseline membrane.
- This year, the project focused on incremental improvements when compared to the baseline for last year. The project team should focus on providing metrics for comparison for each graph provided. For example, the project team should show what an acceptable hydrogen crossover level is and how it compares against the measured level. The continuity between samples/graphs need to be clarified. It is unclear what the conditioning process is or how it can be used as a performance metric if it changes per test. Although this year's work was ambitious, it seems that only one sample performed better than the baseline, and it needed to be conditioned through five cycles to achieve this result.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- The authors explained that they represent a polymer research and development company focusing on low-technology-readiness-level (low-TRL) efforts of approximately TRL 1–3. The team established a collaboration with Proton Onsite to help with incorporating these materials into an electrolyzer and conducting performance testing. Proton Onsite is also helping to address hydrogen–oxygen crossover in their cells. This is a smart collaboration and helps round out the technical capabilities of the team, providing a balance of strong polymer/chemistry skills and strong skills for engineering/deploying electrolyzers.

- Proton Onsite is a strong partner to help keep this project focused and informed. The project leads should consider asking the project manager at Proton Onsite for advice on how to approach this work more systematically.
- The project has a good collaboration partner who is a leading manufacturer with a commercial presence in this area.
- The collaboration with Proton Onsite is good.
- Proton Onsite is a solid partner for this project. The only small critique is that it is unclear how this project fits into Proton Onsite's vision moving forward.
- This project is not really aimed to be involved with other institutions. Proton Onsite is supposed to be involved later in the effort and has not been a major part of the project yet.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is right in line with the efforts toward what the Fuel Cell Technologies Office (FCTO) aims to do: lower the cost of hydrogen production. It could make units easier and cheaper to produce and get more electrolyzers out into the market, which would be a win-win for the renewable energy sector.
- The performance, durability, and cost of membranes are very important to advancing PEM electrolyzers.
- A promising alternative membrane will lead to quicker transition to commercialization.
- The collaboration with Proton Onsite will ensure this work is relevant.
- The efficiency and durability of low-temperature PEM electrolysis is aligned well with DOE and H2@Scale goals. However, even with modest efficiency improvements, products of this research may not be introduced into Proton Onsite's systems unless the project also meet cost targets. The presentation and work seem to be lacking in this area.
- The project supports the general goals of the H2@Scale program, specifically, to create technologies that enable the deployment of hydrogen energy. The project, as presented, is missing any links to the H2@Scale program goals, technical targets, etc. The project does not list any milestones or other metrics that could be used to assess how well it supports the program targets/goals/metrics. This is one aspect of the project that needs to be improved for next year's Annual Merit Review.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future work looks good.
- The proposed future work appears adequate.
- The project has a good plan for scaling up and working toward mass manufacturing. Hydrogen crossover is not addressed in future work.
- The project team should stay focused on the down-selected materials that they have found. This focus will help the project partner assess progress and meet the project's goals.
- Future work is described, briefly, on slide 17. It seems the plan is to continue with developing the material sets described in the presentation. The authors describe more casting trials to assess performance/ consistency. During the oral presentation, the authors mentioned how well this approach was working for assessing scalability. The authors also indicate they will perform a cost analysis. These general plans all seem fine at face value but lack useful detail. The future work plans would be improved if there were technical targets, metrics, or other performance goals included. For example, "optimizing cell design" is an okay future plan, but it would be improved if we knew what the performance targets were that the authors wanted to hit (even if the optimized cell does not get one there). In general, the lack of technical targets/ metrics in this work makes it difficult to assign a better score to many facets of this project. It would be an area to improve for next year's presentation.
- The project plans to do a down-select of the approximately 19 membranes the team is currently working on in Phase IIB. The materials will then be scaled for prototyping in a PEM electrolyzer with Proton OnSite.

More details into how that down-select will be done and in what timeframe would have been helpful in understanding how this project moves ahead in the near future.

Project strengths:

- This is a nice approach for developing polymer materials for PEM electrolyzers. The materials presented seem to perform better than Nafion in some aspects. The materials seem to be durable, performing for ~900–1000 hours of testing. The partnership with Proton OnSite seems to round out the technical skills of this team, making for a very robust and effective partnership.
- Improving efficiency while maintaining durability and reducing costs is critical for PEM electrolysis. The cells/stack make up a large percentage of the overall system cost, so the area of focus in this project is excellent. Tetramer has a strong partner with Proton OnSite, so Tetramer should tap into Proton OnSite's expertise in project management as well.
- This effort has a very specific and targeted task: progress beyond the capabilities of Nafion materials. The focused goal is an advantage in that it keeps the project on task, and it aligns with FCTO goals of getting more electrolyzers deployed.
- The project has a strong approach to polymers and strong experience with polymers.
- The approach, accomplishments, and partners are all strengths of the project.
- The project has a very solid approach to developing a new membrane.

Project weaknesses:

- The project does not list any technical targets, goals, or metrics for either its own work or from the H2@Scale program. It is difficult to assess this work without knowing targets. This is an area that should be addressed for next year's presentation. Currently, there is no cost analysis on the polymer materials or manufacturing costs. Even a simple analysis can serve as a "gut check" as to whether the systems can be commercialized if the performance can be engineered to meet technical targets. This is another area that should be addressed for next year's presentation. The project did not list any milestones or go/no-go decision points. It is difficult to assess progress without having the milestones included. This is a third area that should be addressed for next year's presentation.
- The project seems to lack initial cost estimates to ensure that the down-selected materials will help reduce the cost of the stack while increasing efficiency and maintaining performance. Showing a lot of V-I polarization curves without providing context of how the improved cells affect the goals (with quantified metrics in units that can be understood by people outside the project) is frustrating.
- No cost analysis was presented. The effort appears to lack measurement and quantification of membrane conductivity and of the mechanical properties of the improved membranes.
- It is not clear whether swelling is under control. Crossover is a concern.
- It is not entirely clear how the next part of the project will occur.

Recommendations for additions/deletions to project scope:

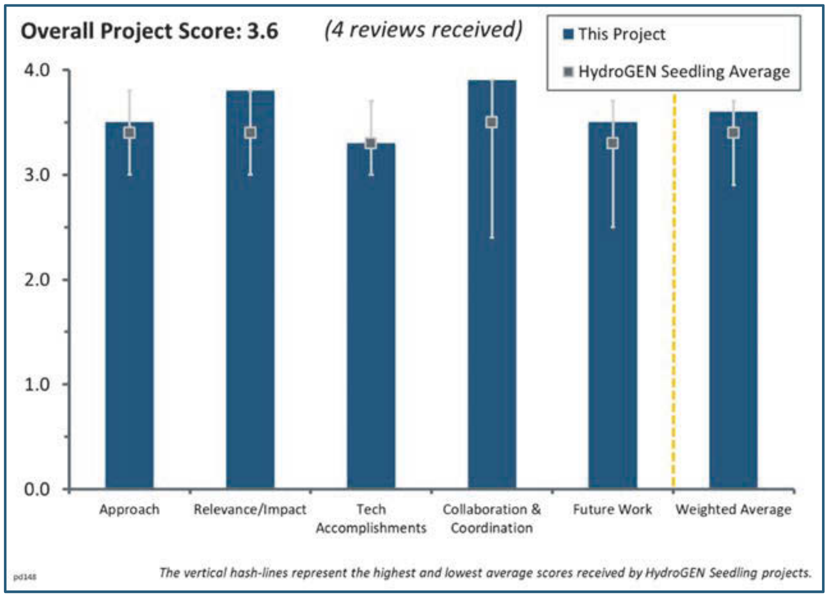
- No change in approach is needed.
- The project team should perform and present a rigorous cost analysis for the membranes. The team should also increase efforts to reduce gas crossover, especially given the reduced membrane thickness. Finally, the team should perform and present quantitative characterization of the membranes.
- A detailed cost analysis of the materials and their manufacturing costs with comparison to current state-of-the-art materials being deployed in electrolyzers should be added to the project scope.
- The project team should clarify when and how the down-select will occur and determine what exactly Proton OnSite will do in this project.

Project PD-148: HydroGEN Overview: A Consortium on Advanced Water-Splitting Materials

Huyen Dinh; National Renewable Energy Laboratory

Brief Summary of Project:

The HydroGEN Consortium's objective is to facilitate collaborations between federal laboratories, academia, and industry to evaluate and accelerate the research and development (R&D) of innovative, advanced materials that are critical and necessary to advanced water-splitting technologies for clean, sustainable, and low-cost hydrogen production. Water-splitting technology pathways supported by HydroGEN include (1) photoelectrochemical, (2) solar thermochemical, (3) low-temperature electrolytic, and (4) high-temperature electrolytic.



Question 1: Approach to performing the work

This project was rated **3.5** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The HydroGEN steering team appears to be working collaboratively and effectively in setting up the Energy Materials Network (EMN), defining capabilities within the network of member laboratories, and defining the barriers to the technologies being pursued. It is still premature to evaluate the overall effectiveness of HydroGEN at this point in time in terms of the role HydroGEN has played in helping to advance the technologies being developed, through projects that utilize the capabilities within HydroGEN.
- Bringing all hydrogen pathways with water-splitting materials under one umbrella is a good approach that can perhaps lead to more focused efforts to efficiently explore and meaningfully assess technoeconomic performance of the materials. The project should consider setting a guidance for near-term success measures (different from U.S. Department of Energy targets) that is common to all pathways.
- The overall HydroGEN effort is undertaken by several dozen groups. The overall approach seems sound, with a mix of projects devoted to hydrogen generation technologies at varying levels of technical maturity: high-temperature electrolysis (HTE)/low-temperature electrolysis (LTE), photoelectrochemical (PEC), and solar thermochemical (STCH) routes.
- The work is well-designed and feasible. It contains useful networking/engagement tools.

Question 2: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- Given that HydroGEN is in the early stages of development, it appears to have a significant impact, considering that nearly half of its 80 nodes are being utilized and that multiple nodes are generally being utilized by a single project.
- Looking beyond the somewhat self-referential nature of this question in this case, HydroGEN fits well within the objectives of DOE and the Fuel Cell Technologies Office (FCTO). Hydrogen, as an energy

vector, impacts many industrial sectors: transportation, energy generation, improving the efficiency of industrial processes, etc.

- The apparent return on investment (i.e., time and money) is very good, and the initial reaction/enthusiasm from the community is impressive.
- The HydroGEN Advanced Water Splitting Materials (AWSMs) effort is in full alignment with the EMN and U.S. DRIVE Partnership objectives. The effort provides a forum and funding for breakthrough and incremental technology development opportunities.

Question 3: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- The fact that about half of the 80+ nodes (capabilities) are being utilized suggests that the interaction with the HydroGEN-supported R&D projects/community is a benefit toward helping DOE realize its goals. It is unclear how to put into perspective the number of users, page views, downloads, etc., as well as the publications and presentations, and whether these are helping DOE achieve its goals/targets. As HydroGEN "matures," a better metric would be clear evidence of how the nodes had an impact in making measurable/ quantifiable benefits toward advancing R&D to meet DOE goals.
- The presented work under consideration, which covered Consortium project updates for the four technology focuses (i.e., HTE/LTE, PEC, STCH), represented the overall HydroGEN program, as well as several projects within the program. This necessarily limited the communication of many distinct accomplishments in any one presentation in the afternoon session. There was the sense that there was abundant progress in the awarded projects, but perhaps a more coordinated effort between the four presentations to avoid redundant information (though there was not a huge amount) would have bought some more time to focus on a few more project highlights rather than relying on the poster sessions to convey that information to the audience. Some of the secondary, visible metrics, such as the use of the data hub (~250 data files in a year), should get more emphasis either on boosting participation or in communicating the complexity of the data contained within the hub. There is ambiguity as to what a single file contains: whether it is a single resistance measurement or a summary from an entire collection of measurements from a unique tool on the beamline. In short, if the scale of the databank were conveyed in person-hours per data file that makes up the ~250 total, that could strike an audience as more impressive/ appropriate than leaving the number of files to remain as an abstract concept, which risks sounding underwhelming.
- The launch of the searchable website on capability nodes and the data hub is an important initial accomplishment. That said, it may be a good idea to revise the effectiveness measure used for these data-sharing tools. The number of files shared does not mean much without some kind of quality check. Also, the ongoing parallel work by Proton and its project team in support of the benchmarking of AWSMs is important and long overdue.
- More time/data is necessary to fairly assess progress in this regard. The initial progress is very positive.

Question 4: Collaboration effectiveness

This project was rated **3.9** for its collaboration and coordination with HydroGEN and other research entities.

- The concept of the EMN has been relatively recently created, and HydroGEN is among the first programs to leverage it. The requirement to leverage the EMN, among other things, makes this inherently a strongly cooperative, collaborative project. Hopefully, the successes of this effort can serve as a model for other similar efforts in the future.
- HydroGEN is doing an excellent job leveraging resources and encouraging collaboration.
- There appears to be a strong sense of positive collaboration among the four national laboratories involved in HydroGEN.
- The organizational leadership structure design across the six national laboratories makes collaboration inherent and necessary across the entire AWSM R&D portfolio. However, it is not obvious whether there is a collaboration with other HydroGEN activities such as H2@Scale.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The proposed work looks great. If possible, the project should accelerate the benchmarking effort so that the results are implemented by the AWSM teams sooner, although it is understood that this point is outside the scope of this review.
- Probably one of the most pressing issues under Proposed Future Work is the development of an effective data management program, not so much in managing the data but in presenting to the R&D community in a format that is of value to the community. Developing benchmarking standard protocols and metrics is another pressing issue to make sure that the protocols for evaluating the various technologies provide an apples-to-apples comparison. Regarding the alignment of core national laboratories with the go/no-go decisions of seedling projects: the role of HydroGEN is to "help" these technologies succeed. One comment, which may or may not be under the "control" of HydroGEN, is the consistency in go/no-go metrics, in terms of a consistency in the quantitative metrics for how far the metrics go toward pushing technology development forward.
- The HydroGEN team should keep up the momentum. It is important to pay close attention to metrics and be sure to adjust to retain interest.
- Most of the projects funded by HydroGEN are still ongoing. The focus was more on current work and results.

Project strengths:

- The collaborative aspect of requiring projects to work with the EMN, creating a search engine for capabilities, and creating and utilizing a data hub are all strengths of this project. The strengths are all tools that may help the impact of the awarded projects to extend beyond their individual groups and to last beyond the scope of the funded projects. Also, it is staggering to see how involved certain node principal investigators are with so many of these projects.
- There is good collaboration among the national laboratories involved in HydroGEN, without the appearance of any turf battles over expertise that may be located within more than one partner laboratory. The identification of a large number of nodes (capabilities/expertise) that are being highly utilized at this early stage suggests that there is good value in the nodes identified so far.
- The project's strength lies in solid leadership and organizational structure, as well as the inherent collaboration across the six national laboratories.
- The strengths of this project lie in the collaboration, resource utilization, and the data storage/sharing (in theory).

Project weaknesses:

- The categorizing of nodes as Categories 1–3, with Category 1 being the most developed and Category 3 being the least developed, is a good strategy. What is in question is how the nodes are funded. For example, if a node is not initially called out in a proposal, it is not funded. That is fine for Category 1 nodes that are not funded because they are the most mature technologically, but for Category 3 nodes, it could be an issue if the node were to be of value to a later funding opportunity announcement awardee but was not fully developed to the point of being of value. Data management in terms of how much data has been made available so far seems very limited, given the level of funding and the number of nodes participating in the projects; the form in which the data is made available seems to be an issue. It is uncertain how to even determine how effective the data management has been to date and how effective will it be going forward.
- The category readiness level classification was confusing. There is an upward increment of technology readiness levels (TRLs) to show increasing maturity, whereas the commercial readiness levels (CRLs) decrease. The project presenters would simply speak of "readiness levels," and the meaning was unclear without more context. On the other hand, the CRL counting down to 1 makes the boundaries of the project scope clear. The classification tops out at CRL 1, so there is clarity in that fixed endpoint.
- Although individual projects have milestones and go/no-go points, the AWSM Consortium lacks clear success metrics at a higher level to guide its pathways and projects.

- The data use metrics were unclear. The metrics of user "engagement" were also uncertain; it is unclear how many of the users are participating and at what level.

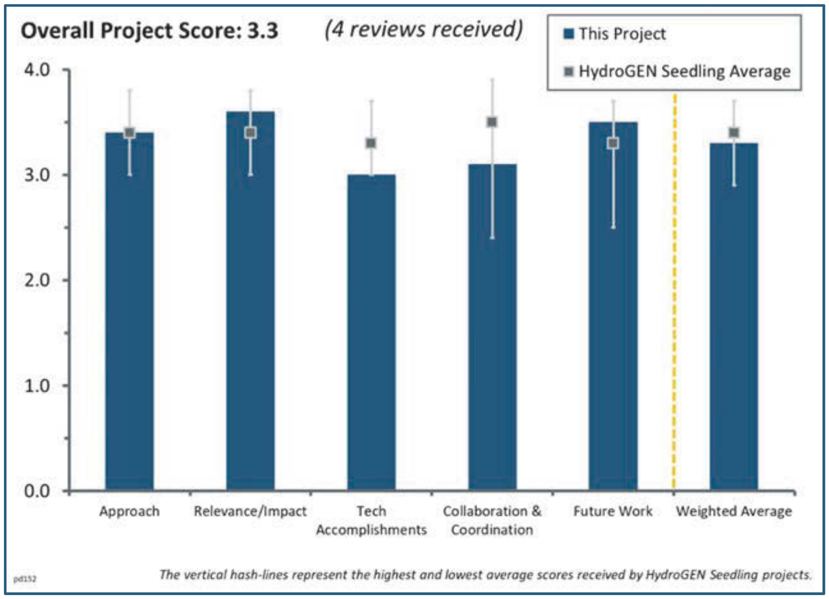
Recommendations for additions/deletions to project scope:

- The project team should consider making a distinction between long-term technologies (e.g., STCH, PEC) and near-term ones (e.g., LTE)—perhaps in some form of TRL numbers, graphics, colors, or financial tags. That way, the reader has a reasonable understanding of the relative commercial readiness and R&D effort level of the various pathways. The project should consider setting near-term success measures or expectations that are common to all pathways.
- Clear metrics for user engagement and activity are recommended.

Project #PD-152: Proton-Conducting Solid Oxide Electrolysis Cells for Large-Scale Hydrogen Production at Intermediate Temperatures

Prabhakar Singh; University of Connecticut

Brief Summary of Project:



The primary objective of this project is to identify novel materials and processing techniques to develop cost-effective and efficient proton-conducting solid oxide electrolysis cells (H-SOECs) for large-scale hydrogen production at intermediate temperatures (600°C–800°C). New proton-conducting electrolytes, tailored hydrogen and oxygen electrodes, and optimized cell designs for lowering the electrode polarization and resistive losses will be developed. Following synthesis and characterization of new electrolyte and electrode materials, they will be used for the fabrication of SOEC single cells and tested for performance and durability. Degradation mechanisms will be developed and materials chemistry and component structures will be optimized to mitigate any degradation.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- This is a good project. It should seek to map physical outcomes as a function of, or a correlation to, chemical “income.” The project could probably improve upon the vertical interaction among team members. For example, the undergraduate student has never had a direct technical conversation with the chief scientist at PNNL. While it is not expected that such interactions should be an emphasis of the project, it does seem like a missed opportunity. The metrics to demonstrate project impact are slightly more evolved than those seen in other projects. For example, instead of just saying the system needs to be “stable,” the project states that the performance degradation rate must be less than 4 mV/1000 h. This specificity is commendable. Some additional thought may need to be expended on the benefit of having “uniform bulk phase composition.” Matter moves as waves, and the periodicity of “defects” should not be overlooked as having no role in this. The technology need not obtain 100% densification. Indeed, having such perfectly dense material may be detrimental to the system. This is nice from a practicality perspective. The idea of using a getter to keep chromium content down in the system seems effective. The preliminary work of varying the chemical constituents in the atmosphere during densification of the electrolyte seems to allow some divergence in the electrical conductivity at higher temperatures. To date, this work has involved only dry and wet conditions of air and nitrogen. The addition of other interesting oxidants could lead to more changes in conductivity.
- This is a sound approach. The sintering aid seems to be working well. It would be good to see some assessment of a sintering aid “sink” or “final resting place.” Given that most of the ZnO vaporizes and some trace Zn must remain, the question remains about where the final ZnO mass accumulates and whether there are any materials that must be avoided to avoid later contamination, degradation, or otherwise detrimental outcomes.

- Evaluating systematic screening of sintering aids is a good approach. Exposure to hydrogen needs to be done to make sure that the sintering aid oxide does not precipitate out along the grain boundaries—and if it does, that it is not detrimental to electrical and mechanical properties.
- The high-performing proton conductor $BaZr_{0.1}Ce_{0.7}Y_{0.1}Yb_{0.1}O_{3-\delta}$ (BZCY-Yb) and ZnO sintering aids have been in high-temperature proton conductor literature for several years. It is unclear where the innovation is, other than in the high-throughput compositional analysis that will be done at NREL and the atmosphere composition effects during sintering. The approach seems incremental but could yield some improved processing steps for high-temperature electrolysis.

Question 2: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- Apparently, dropping the sintering temperature by even 100ºC for the electrolyte greatly changes the sintering behavior. It also leads to cheaper heating elements, cheaper insulation, and other benefits. Being able to operate between 550º and 750ºC is important because this brings the technology into a space in which some material development efforts may be shared with concentrating solar power, which is another renewable energy technology that is also targeting 750ºC operation. In the long run, this could help develop the critical mass needed to drive costs down. The milestones seem okay, being SMART (specific, measurable, assignable, realistic, and time-related). The go/no-go decision point is especially strong. The value of the achievement could be better emphasized by perhaps also including some comparison of the change(s) versus the state of the art (i.e., a relative percent change).
- Yttrium-doped barium zirconate (BZY) is notoriously difficult to densify, so any improvements in processing could benefit other uses of the material. Lowering the sintering temperature and times will lower processing costs and throughput times.
- This project is extremely relevant with a high impact and makes a very good case for hydrogen production via high-temperature H-SOECs.
- Proton conductor-based electrolysis aligns with DOE objectives. The opportunity to produce dry hydrogen is very attractive.

Question 3: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- Meeting the conductivity target is a good accomplishment. The approach to modifying the dopants to achieve target conductivity is well-thought-out and well executed.
- The project goals are on track. Good progress has been made on milestones.
- The addition of ZnO produces a visually stunning result in sintering at 1350ºC. Tin has also been evaluated. The strategy/scientific rationale behind which elements are selected for the sol gel synthesis could have been better articulated. While it is obvious that NREL is providing support for the "...investigation of combinatorial libraries of Y-substituted BaZrO3," it is not clear whether the effort is purely combinatorial. In other words, it would be good to know whether all the combinations defined by mathematics are being tested or whether some scientific intuition (or better yet, some scientific hypothesis) is being tested. Three of the five milestones have been met so far for budget period 1. It seems likely that some of these milestones were perhaps not challenging enough. The project should consider incorporating some "stretch" milestones in the future such that, if these are met by the researchers, it will be considered an outstanding achievement. If, however, the stretch milestones are not met, the project would not be punished. This will provide some internal calibration for what the project team truly considers challenging in this vein of research.
- There is no apparent evidence of significant experimental progress. It seems that some fabrication basics are still being ironed out. The material sets at play are not novel, so more detail is to be expected on the processing studies, as well as more progress on them. It is unclear why an oxygen-ion-conducting SOEC (O-SOEC) is being tested as a benchmark. The materials and temperature of operation are different. It

would make more sense to compare H-SOECs using more conventional high-temperature processing (or simply literature data) as a benchmark.

Question 4: Collaboration effectiveness

This project was rated **3.1** for its collaboration and coordination with HydroGEN and other research entities.

- Collaboration seems to be effective based on milestone progress and reports from each group. Work appears thorough, but also independent.
- Good interaction is occurring with the nodes.
- NREL work will be valuable when the data from the laboratory can be used to inform the University of Connecticut (UConn) fabrication and data collection. INL helped UConn make dense electrolytes. It is to be hoped that these collaborations with capable EMN nodes will bear more fruit in the months to come.
- The collaboration with INL to receive half cells appears effective. The role of PNNL is not clear from the presentation. PNNL could contribute in the immediate term by determining the stability of the electrolyte compositions in a steam environment at the target operating temperature.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The proposed future work is a logical extension of the existing work. Some of the proposed future work addresses the comments and concerns listed in prior review criteria. There is a good use of SMART metrics for future work. The impetus for the technical and scientific undertakings seems clear, insofar as it relates to the project objectives, but the scientific hypotheses being tested could be better (explicitly) defined.
- There is good momentum, and project collaboration seems to be functioning well. The future work goals are reasonable and seem achievable at present.
- The Phase II work plan includes some specific targets and seems rational.
- The proposed work is adequately enumerated. Stability in steam is planned. It is critical to evaluate the stability of both the electrolyte and the possible precipitates from the post-hydrogen-exposure sintering aid. While the hydrogen produced is expected to be dry, conducting a stability test in a hydrogen–steam environment is recommended. It is also important to characterize the proton transference number in the proposed operating temperature range. These materials are known to exhibit proton, oxygen, and electronic conduction, all of which vary with temperature and oxygen partial pressure. The investigation of such properties will help decide suitable operating conditions to achieve high efficiency.

Project strengths:

- This is a good project that is leveraging both new materials and new ways to combine those materials. It is pursuing these innovations with a mindfulness for reducing the demands placed upon the manufacturing infrastructure. Innovations developed at the national laboratories are being exploited effectively. The principal investigator is clearly an expert in the project team's field of research.
- Collaboration with other nodes is good. The plan adequately addresses potential pitfalls of this materials set.
- The high-throughput capabilities at NREL should help to provide a strong direction for this project, assuming that the compositional space is rationally defined.
- This is a good team, and there is good collaboration.

Project weaknesses:

- This project seems to suffer from a lack of focus and progress. Materials processing for lowered temperature fabrication of dense parts can be impactful, but it must be done meticulously and documented and communicated well to have meaningful impact.

- Explicitly stating the scientific hypotheses in sets of the null condition and the alternate would provide additional transparency into what is driving the experiments. The vertical integration of project participants could be improved.
- The project is very dependent on the sintering aid for electrolyte density. Attention to the sintering aid accumulation/detection is encouraged.
- The priority for materials stability testing needs to be high.

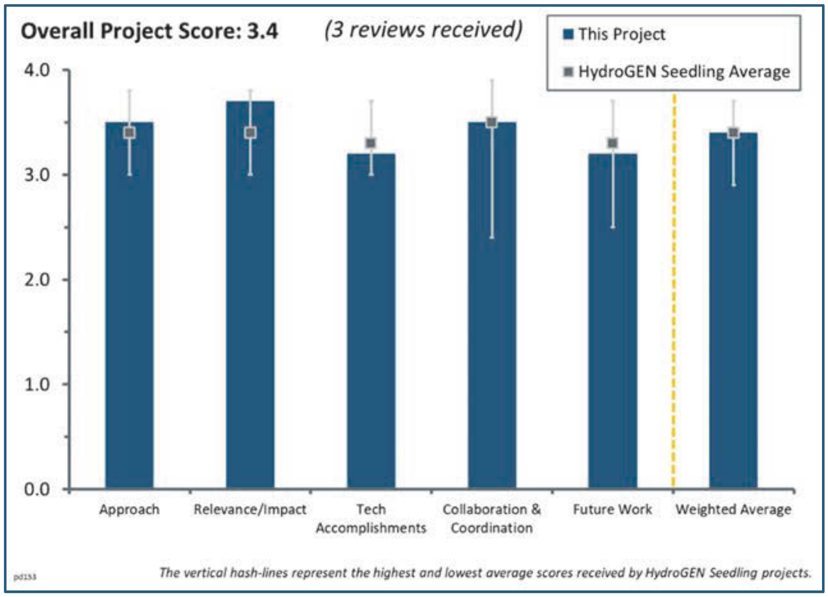
Recommendations for additions/deletions to project scope:

- Overall, the project scope is very good. Phase II needs to include a thermomechanical characterization of these electrolytes. They are known to be mechanically weak.
- The project may benefit from a more defined processing plan to help make faster progress in the experimental work.
- The project team should consider adding the ability to sinter under the influence of applied electric/ magnetic fields.
- The project should address a sintering aid sink, when possible.

Project #PD-153: Degradation Characterization and Modeling of a New Solid Oxide Electrolysis Cell Utilizing Accelerated Life Testing

Scott Barnett; Northwestern University

Brief Summary of Project:



Solid oxide electrolysis cells (SOECs) have the potential for high electricity-to-hydrogen conversion efficiency, but these cells lack long-term stability, particularly at high current density, and the degradation mechanisms in SOECs are poorly understood. The project aims to develop mechanistic degradation models that realistically predict long-term solid oxide electrolysis cell (SOEC) durability, using input data from accelerated electrochemical life testing combined with quantitative microstructural and microchemical evaluation. Also, a promising SOEC cell type with high performance will be further developed. The understanding achieved by combining experimental results and theory will be used to guide improvements in long-term SOEC durability.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The approach is clearly laid out. The principal investigator's group is leveraging its degradation model experience with solid oxide fuel cells (SOFCs) and applying it to SOECs. The barriers are identified, and appropriate project partners at LBNL and INL were selected to improve the odds of success. The model selected predicts oxygen potential in order to anticipate conditions that lead to degradation, when compared to experimental testing.
- The extension of knowledge about SOFC degradation to SOECs is reasonable and logical. The model's methods/approach and boundary conditions are logical.
- The prediction of oxygen potential across the electrolyte is a useful tool for determining critical parameters in improving electrolyzer stability.

Question 2: Relevance/potential impact

This project was rated **3.7** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- Oxygen electrode delamination is a well-known challenge in electrolyzer development. This project addresses one aspect, namely, high oxygen partial pressure at the electrolyte–electrode interface. The estimation of interface oxygen pressure using measured electrode polarization provides predictive capability to select operating conditions without catastrophic cell failure. This model has applicability independent of the cell design and materials set.
- The potential impact of this project could be exceptional if it generates tools that could be used broadly in SOEC design. That would be an exemplary case of a Fuel-Cell-Technologies-Office-funded project

furthering not only its own niche goals but additionally benefiting the high-temperature electrolysis community at large.
- This project is very relevant, particularly considering the fact that higher current densities are not always detrimental. The coupling of current density and effective oxygen partial pressure at the electrode is important.

Question 3: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- Though the project is behind on many of its milestones (partially but not 100% complete), it appears that that could be due to delays in the cell fabrication that delayed planned testing, which is not uncommon. The approach is strong, so this project should be able to stay on track and deliver additional impactful information. The metal-supported SOECs at LBNL could be promising if further improvements are made. The INL-made cells should add an additional level of model validation as well.
- The modeling work seems to have gone well and is on the right track. However, the presentation does not show a pathway to accelerated testing—which is the title of the project. It would be helpful to define the accelerated testing, as well as the basis of such test methods, so that the test method ensures the degradation mechanism remains the same as in normal testing.
- Progress seems to have built up slowly, with some slipping, but overall, it is reasonable and promising.

Question 4: Collaboration effectiveness

This project was rated **3.5** for its collaboration and coordination with HydroGEN and other research entities.

- The cell developments in parallel at LBNL (metal-supported), INL, and Northwestern University add significant value to the degradation model efforts, assuming that there is a useful agreement of failure modes that can be linked back to the oxygen activity upon which the Northwestern University model is predicated. Hopefully, this yields a more robust model.
- The collaboration with LBNL to test metal-supported cells in electrolysis mode is appropriate, and the performance results are encouraging.
- The Northwestern University, INL, and LBNL collaboration appears to be functioning well. The use of data from Data Hub for model verification would be very encouraging.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Incremental advances in the understanding of degradation mechanisms are very useful. No leaps in understanding are expected, but hopefully, reasonable predictions of SOEC lifetime expectations, or at least optimal operating points, will result from this. The model will almost certainly hit additional hurdles, but progress is reasonable, and future work seems manageable for the team.
- The future work gives some general details about the tasks that remain ahead. With much work remaining on the first iteration of the degradation model, this level of detail is understandable. However, there is much similarity between the proposed future work for budget period 2 and 3.
- The definition, justification, and execution of accelerated testing must be included. The effect of the ceria barrier layer may be useful in the model for oxygen potential prediction. The other tasks seem fine.

Project strengths:

- This project leverages the team's experience with degradation model development and pairs that with SOEC development from INL and LBNL.
- The predictive model for oxygen potential is a useful tool. The new oxygen electrode performance and stability appear excellent.

- This is a great team with a diverse set of well-made cells. The researchers have a good data set with which to work.

Project weaknesses:

- The model may not account for enough variables to truly build degradation mechanism insight, but it should be able to predict reasonable expected lifetimes.
- This project's weakness is that it still requires a significant amount of degradation data to build and validate the degradation model.
- The accelerated testing protocol needs to be defined.

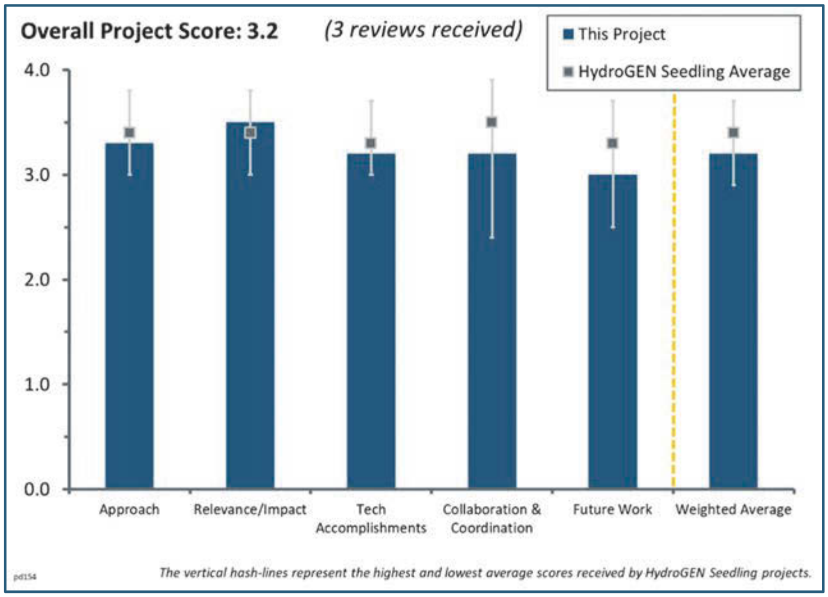
Recommendations for additions/deletions to project scope:

- The project team should keep up the good work.
- No additions/deletions to the project scope are requested.

Project #PD-154: Thin-Film, Metal-Supported High-Performance and Durable Proton–Solid Oxide Electrolyzer Cell

Tianli Zhu; United Technologies Research Center

Brief Summary of Project:



This project is developing a thin-film, durable metal-supported solid oxide electrolysis cell (SOEC) using a proton-conducting electrolyte at targeted operating temperatures of 550°C–650°C. This advanced SOEC will provide a highly efficient, cost-competitive high-temperature electrolysis process for hydrogen production. Initial efforts are on demonstrating the feasibility of the proposed concept by further advancing metal-supported single cells based on work completed previously for solid oxide fuel cell (SOFC) applications. Cell fabrication, especially electrolyte deposition via reactive spray deposition technology (RSDT) and suspension plasma spray (SPS) processes, is a focus.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The approach for this project attempts to combine low-temperature deposition techniques to fabricate electrolytes of highly refractory yttria- and ceria-doped barium zirconate (BCZY) material on metal supports. This type of approach has been used successfully for metal-supported SOFCs in the past. The tasks for budget period 1 seem appropriate for evaluating whether the fabrication and testing progress is on track to deliver more refined data in budget period 2, or if unforeseen processing bottlenecks could jeopardize the success of the project.
- The overall approach is promising. Metal-supported design has the possibility of being a good option for hydrogen production at scale.
- The project follows a solid, logical approach and has a good team.

Question 2: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The project team pursued a less expensive fabrication path to high-temperature proton-conducting electrolyzers for hydrogen generation. Addressing the cost issues while maintaining performance fits with the HydroGEN consortium's goals, and the project pulls in several Energy Materials Network (EMN) nodes.
- Proton-conducting SOECs are very relevant; it is hard to debate that fact. Whether cost/durability targets will be met may be debated, but this work seems to indicate that there is good progress in that direction.
- If successful, metal-supported cell design could be a very promising option for large-scale hydrogen production, in terms of cell scalability and low cost.

Question 3: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- Complex, multication materials are difficult to deposit on a support. The success of getting a dense layer on a metal support within a single phase is a good accomplishment.
- The project is on track to meet its stated goals and DOE goals.
- It is challenging to judge the progress of electrolyte fabrication without cell data. Focused ion beam (FIB)/scanning electron microscope (SEM) imaging can show miniscule dense regions but cannot capture the deleterious effect of pinholes or other defects in the membrane. Electrical performance is the key to verifying that electrolyte and electrode morphologies are in spec, so seeing that data is anticipated. Only one full cell test is shown, and it seemed to suffer a cell or seal failure and never reached a significant open circuit voltage, nor was it run in electrolysis mode. Those milestones are not due until the fourth quarter and are necessary for a go/no-go decision, but until that data comes in, it seems that fabrication progress is satisfactory.

Question 4: Collaboration effectiveness

This project was rated **3.2** for its collaboration and coordination with HydroGEN and other research entities.

- The team uses several EMN hubs. Lawrence Berkeley National Laboratory (LBNL) was utilized for its expertise in metal-supported cells, Idaho National Laboratory (INL) for fabrication, and the National Renewable Energy Laboratory for modeling work.
- Collaboration with INL and LBNL was appropriate to engage laboratories with the right set of skills.
- It is unclear how well the collaboration is functioning. The project is progressing well, but work seems very independent at the present time.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work has appropriate objectives.
- Negligible detail is given for tasks in budget periods 2 and 3. The project team should also consider how compositions or processes might be improved; some detail should be given, based on what is known now, i.e., at about 75% through budget period 1.
- The team has good performance targets, but it is uncertain whether targets can be met at the current pace of the project.

Project strengths:

- Metal-supported cells have the best potential for large-scale hydrogen production. Prior experience in an Advanced Research Projects Agency–Energy (ARPA-E) project of similar cell design gives the team background technical information on which to build.
- The project leverages technology solutions that have proven success for SOFCs, based on similar materials.
- This is a good team with a good start and good targets.

Project weaknesses:

- If the processing routes do not produce functional cells quickly, the project cannot effectively proceed past the first go/no-go decision point.
- Collaboration could be stronger or the strength better communicated. Sintering and barrier coating work needs to be strengthened.
- Electrolyte density appears to be an issue, but there was no specific approach defined to address this.

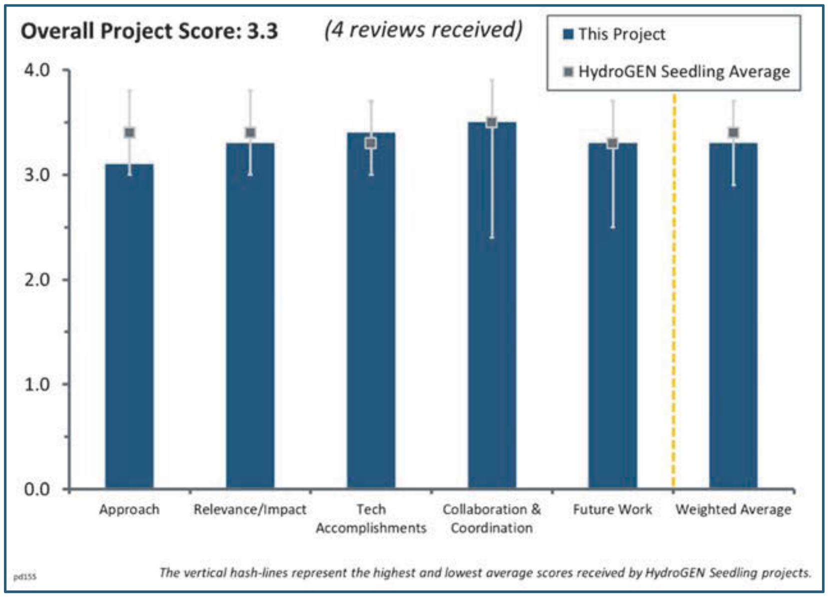
Recommendations for additions/deletions to project scope:

- No change to the scope is necessary.

Project #PD-155: High-Efficiency Polymer Electrolyte Membrane Water Electrolysis Enabled by Advanced Catalysts, Membranes, and Processes

Kathy Ayers; Proton OnSite

Brief Summary of Project:



This project will develop an advanced, highly efficient polymer electrolyte membrane water electrolysis (PEMWE) membrane electrode assembly (MEA) by addressing membrane, catalyst, catalyst layers, and their interfaces. Four areas affecting cost and efficiency that will be developed include (1) thinner membranes, (2) lower catalyst loadings, (3) optimized gas diffusion layer and porous transport layer materials and structures, and (4) increased operating temperature. Successful demonstration and integration of these four areas require a deeper understanding of the scientific and technical aspects of PEMWE MEAs. Proton Onsite will partner with Tufts University and Oak Ridge National Laboratory—with support from the National Renewable Energy Laboratory (NREL) and Lawrence Berkeley National Laboratory (LBNL)—to integrate advanced cell designs and materials and fundamentally characterize performance.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- Researchers are addressing cost barriers associated with PEM technology through cell design and material optimization. Their final deliverable is stated to be an "advanced electrolysis stack producing H_2 at 43 kWh/kg and at costs of $2/kg H_2." The project's approach involves optimizing the catalyst composition, developing thinner membranes, and optimizing the interfacial properties. These parameters are expected to improve water transport and prevent catalyst migration for improved system performance. The project is separated into three experimental tasks:
    - Task1: Membrane processing, with a goal of characterizing properties and measuring changes that occur during operation
    - Task 2: Advanced MEA fabrication, resulting in the development of formulations and deposition parameters, as well as the characterization of water distribution using X-ray computed tomography (CT)
    - Task 3: Catalyst development, involving synthesis of alloyed catalysts containing Ir and Ru and analysis of the catalysts with microscopy to evaluate performance

  These tasks all partner with HydroGEN consortium nodes to accomplish the stated goals. The approach is very reasonable, and the results are promising. For example, the project team's approach has successfully demonstrated good MEA performance at 1.85 V. The approach has also demonstrated that alloying Ir and Ru provides a more active and durable catalyst. The team's use of in situ CT allows for the imaging of catalyst layers and bubble formation on the gas diffusion layer. This will help with optimizing the electrode and reactor structure for improved performance. However, the approach still relies on expensive precious metal catalysts (Ir and Ru); a true reduction in cost barriers requires precious-metal-free catalysts.

- The project clearly identifies the challenges to durable and high-efficiency membranes for hydrogen generation through water electrolysis. The scope of work as initially outlined exceeds the allocated resources by identifying five major design parameters and multiple diagnostic tests. However, delving into the project reveals appropriately re-scoped work to yield meritorious data within existing resource constraints.
- Thinner membranes, advanced catalysts, and operation at higher temperature have good potential to improve efficiency.
- The approach is supposed to address critical barriers such as long-term durability and higher defect sensitivity. In the "approach: innovation" section, the researchers listed standard terminology that has been used over the years to address essentially the same issues. It is hard to see what would be the novelty of this approach that would distinguish it from past efforts, unless this is what the team terms a "holistic" view of the problems.

Question 2: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The project aligns well with the DOE Hydrogen and Fuel Cells Program (the Program). The project team's combination of membrane, cell, and catalyst optimization should meet the target production cost of \$2/kg H_2 by the fourth quarter (Q4). Moreover, the development of in situ CT provides key insights into the structural changes that occur at the electrode surface and also shows how gas bubbles accumulate. This information can be used to further optimize cell design for improved performance and lower overall costs. The project team's current work is extremely promising and is on target to meet DOE goals, but improvement could be made by eliminating or reducing precious metals in the catalyst structure.
- The project is relevant, given the potential for complex, integrated system benefits when the performance at component interfaces is more thoroughly understood. Within the available resources, this project has the potential to achieve the production target of \$2/kg H_2 by reducing the inefficiencies at these component interfaces, as well as improving cell-level performance.
- Reaching the DOE hydrogen production goal of \$2/kg H_2 is very relevant to hydrogen refueling infrastructure. The project also leverages the HydroGEN consortium.
- This project aligns well with the objective of the Program and the HydroGEN consortium.

Question 3: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- The project team has successfully met the Q1 and Q2 milestones and is making progress toward the remaining Q3 and Q4 milestones. Specifically, the team has exceeded Q2 performance metrics and was able to operate the cell with 2.2 A/cm^2 at less than 1.85 V. There is an excellent use of HydroGEN nodes to accomplish in situ CT and rotating disk electrode studies of catalyst degradation. This data will hopefully allow for further optimization of cell parameters for improved overall performance. The authors claim they are close to the go/no-go criteria (Q4 milestone) of 1.8 A/cm^2 at 1.7 V cell potential operating at 90°C. This would require an approximately 100 mV decrease in operating potential compared to the current performance data.
- Significant progress was made in the first year, considering the late start. Tomography insight into the electrode structure and water management is valuable for the future design of electrodes. The MEA performance of 1.85 V at 80°C was demonstrated within the first two quarters. The project seems to be on a good path to meet the Q4 projected milestone of 1.8 mA/cm^2 at 1.7 V.
- The hardware test results demonstrate that both the prime vendor and project partners have made notable progress. Catalyst performance and diagnostic test results are on track to effectively inform manufacturing technique development for scaling this performance from the catalyst level to the cell level with potentially thinner membranes.
- The team has met the Q2 milestone performance target of 800-hour durability at high current density.

Question 4: Collaboration effectiveness

This project was rated **3.5** for its collaboration and coordination with HydroGEN and other research entities.

- The project effectively leverages Energy Materials Network (EMN) nodes through the LBNL and NREL for catalyst activity screening and degradation measurements, as well as membrane hydration modeling and measurements. Moreover, cell characterization with in situ CT is a unique capability that provides insight into the catalyst layer structure and the formation/movement of bubbles across the electrode surface. This technique will provide extremely valuable information on how to potentially optimize the cell architecture to improve performance.
- This work both replicates catalyst performance demonstrated in previous research by other firms and increases the available relevant empirical data. Including both successful and unsuccessful catalyst formulations in the EMN leverages heritage efforts. Executing standardized testing increases the potential for replication of results by research partners, thereby augmenting the pace of development.
- The project effectively leverages the capabilities of two EMN nodes.
- There is excellent collaboration among the participants.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- Developing an MEA is not a trivial task. Overall, this activity proposes to investigate thinner membranes, novel OER catalysts, and refined electrode deposition and inspection methods to deliver this improved MEA to satisfy the DOE performance metrics. Near-term work focuses on membrane processing to incorporate catalyst advances into an interim MEA while investigating thinner membranes as an external partner's parallel effort.
- The proposed future work is in excellent agreement with the approach and ongoing work.
- There is a good plan in place to meet the go/no-go milestone.
- The project is on track to meet budget period 1 milestones and a target performance of 1.8 A/cm^2 at 1.7 V cell potential at 90°C. This will achieve the DOE goal of \$2/kg H_2. The proposed future work/next steps involve additional membrane processing for mechanical evaluation at LBNL and in situ electrode imaging via CT. This tomography will be used to guide the modeling at LBNL. Parallel efforts will evaluate and define processing parameters to achieve thinner membranes, and high-activity catalysts can be integrated with NREL support. There is a desired reduction in operating temperature to meet target performance, although the researchers claim they are close to achieving 1.8 A/cm^2 at 1.7 V. This future work is reasonable, but it could be improved by considering how to reduce or eliminate precious metals from the catalyst composition.

Project strengths:

- This project is doing an excellent job of improving the performance of precious-metal catalyst systems and characterizing the evolution of catalyst layer and bubble distribution along the electrode surface. These efforts are well integrated with EMN nodes, and the collaboration seems to be working well. The work has currently produced very high activity numbers and is on track to meet DOE goals.
- The team executing this task is experienced and understands the multiple interfaces under investigation.
- This is a well-established effort executed by the leaders in this field.
- This project addresses critical issues related to PEM water electrolyzers.

Project weaknesses:

- This activity is attempting to cover a wide scope of work and has the risk of spreading resources too thin to complete the assignments. Decreasing membrane thickness typically decreases durability and challenges the system for high-pressure applications.
- The project team did not discuss the class of membrane materials used and how the risk of increased cross-over and reduced mechanical strength of the thinner membrane is mitigated.

- The only real weakness is the reliance on precious-metal catalysts. This could be addressed in future budget periods or be the subject of an entirely new project.
- A more diverse set of tools for characterization should be used.

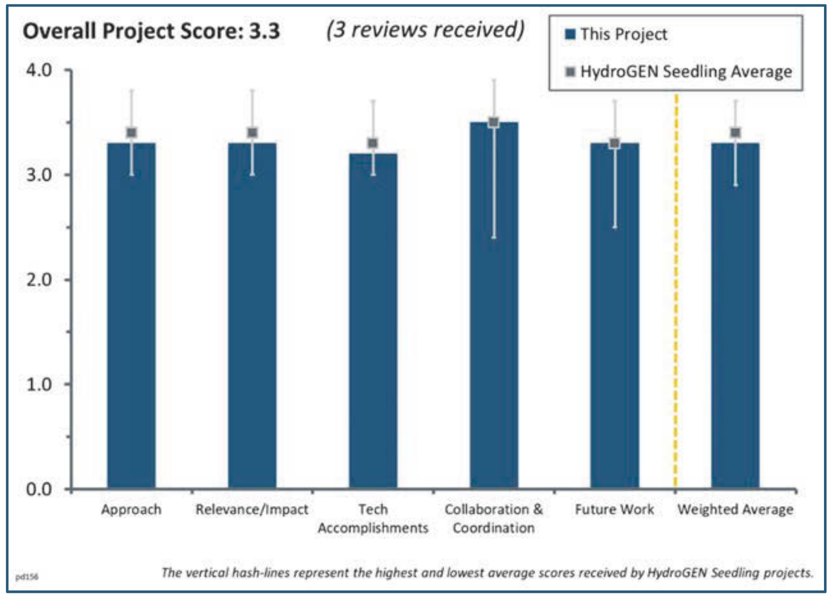
Recommendations for additions/deletions to project scope:

- The scope of the project is fine for a precious-metal-based catalyst system. However, once cell and membrane parameters have been optimized, future efforts should focus on creating catalysts with reduced precious-metal content.
- It would be valuable for the team to include this new membrane in a heritage high-pressure electrolyzer to investigate the potential for inclusion within high-pressure applications.
- It is recommended that the project team add metrics for evaluating the membrane: conductivity, mechanical strength, gas cross-over, etc.
- In dissolution studies, more sophisticated methods should be used, such as online inductively coupled plasma–mass spectrometry (ICP-MS).

Project #PD-156: Developing Novel Platinum-Group-Metal-Free Catalysts for Alkaline Hydrogen and Oxygen Evolution Reactions

Sanjeev Mukerjee; Northeastern University

Brief Summary of Project:



The aim of this project is to develop (1) stable, high-conductivity, and high-strength anion exchange membranes (AEMs) and ionomers, (2) stable and active platinum-group-metal-free (PGM-free) catalysts for hydrogen and oxygen evolution reactions (HERs/OERs), and (3) high-performance electrode architectures that together can begin to achieve the low-cost advantages of AEM electrolyzers. This effort is focused on materials development by tailoring synthesis and composites with supporting efforts in computation and characterization. The project work—and collaborations with the University of Delaware, Advent North America, the National Renewable Energy Laboratory (NREL), Lawrence Berkeley National Laboratory (LBNL), and Sandia National Laboratories (SNL)—strives to enable a clear pathway to achieving hydrogen costs of less than $2 per kilogram, with an efficiency of 43 kWh per kilogram, via AEM-based electrolysis.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- This project is rather ambitious and plans to address improving AEMs, developing novel PGM-free catalysts that show stability and activity for both cathodic and anodic HER and OER reactions, and integrating these into high-performance electrolyzer electrode assemblies. The project impact and overall goal is to achieve a clear pathway to hydrogen production at <$2/kg with an energy efficiency of 43 kWh/kg hydrogen. Catalyst development will be conducted at Northeastern University. HER catalysts will include Ni-based oxides, functionalized mono-metallic, and nitrogen–carbon–metal catalyst stems. OER catalyst development will include double-layer metal oxides on Raney Nickel. In situ X-ray absorption spectroscopy (XAS) will provide key insights into catalyst electronic structure and performance. Membrane development and gas diffusion electrode development will be conducted by sub-awardees University of Delaware and Advent North America. The project will leverage NREL's expertise in membrane electrode assembly (MEA) and testing, LBNL's capabilities for small-angle scattering and transport modeling, and SNL for interfacial modeling. The project scope is large, but the work breakdown seems reasonable and effectively leverages the Energy Materials Network's (EMN's) capabilities for development of high-activity electrochemical systems.
- This is an excellent approach in tackling the most challenging issues in electrochemistry. The lead researchers rely on fundamental principles to resolve complex interfaces to design new materials for the HER and OER. In addition, highly sophisticated characterization tools are employed to get ex situ and in situ feedback. All three crucial aspects are being covered by this work: PGM-free catalysts, novel membranes, and electrode structures.
- The project has an exceptionally logical approach of dividing the problem into manageable sub-elements and distributing these sub-elements across a team of collaborators. It would be beneficial to have some

verbiage on how to eventually implement these innovations on the industrial scale to guide this work from the laboratory into practice.

Question 2: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The project is extremely relevant to the HydroGEN consortium mission of sustainable and cost-competitive hydrogen generation at $2/kg. Moreover, the emphasis on precious-metal-free catalysts will further lower the costs associated with water-splitting systems. The project also effectively leverages HydroGEN capabilities through synchrotron-based X-ray characterization, MEA preparation, and modeling.
- This fundamental work solidly addresses the catalyst and membrane barriers to AEM electrolysis. Membrane durability and cumulative performance of the proposed formulation of the AEM MEA will determine the impact of this technology. It would be of benefit in future proposals to expand the list of potential salts in the feedstock water. This has the potential to reduce water-processing requirements, thus expanding the potential geographical regions into which this technology may be deployed.
- If successful, this project will have rather high impact.

Question 3: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The project has successfully completed first quarter (Q1) and Q2 milestones of demonstrating high-performance, precious-metal-free catalysts for both HER and OER reactions. Synthetic scale-up has produced 5-gram batches and delivered them to consortium collaborators for X-ray characterization and rotating disk electrode (RDE) testing. Novel MEA materials have also been synthesized, and initial evaluations have begun. This project is well on its way to creating active, precious-metal-free water-splitting catalysts.
- Given that this project had a late start, significant progress has been made toward the DOE goals. For the first two quarters, the project met the milestones and delivered the three 5-gram batch samples of Ni-MO_x/C catalysts, as well as one batch of Ni-N_x/C HER catalysts, for RDE and single-cell tests. They showed overpotential of η=300 mV at 500 mA/cm^2 and 2 A/cm^3 (HER). In addition, a membrane based on PAP-TN was synthesized. Reaction and polymerization conditions are still to be optimized.
- The work clearly identifies improved non-PGM HER and preliminary OER catalyst performance under a range of applicable conditions with supporting empirical data from the collaborating partners. The project appears to be on schedule, with near-term work to elucidate the performance of the new ionomer and AEM formulations.

Question 4: Collaboration effectiveness

This project was rated **3.5** for its collaboration and coordination with HydroGEN and other research entities.

- The project has demonstrated good collaboration and use of EMN nodes. For example, the team has used modeling results from SNL to understand ionomer membrane properties. These results will be used to further optimize the ionomer composition to improve performance. Modeling and X-ray scattering results from LBNL have provided key information on AEMs as a function of hydration and applied current density through the electrochemical cell. NREL capabilities will be leveraged for MEA preparation and evaluation.
- There is excellent coordination between the collaborators.
- This project includes a comparatively large number of collaborators: three contract awardees and three national laboratories. Developmental materials, modeling results, and test results all flow among the group well enough to deliver punctually on the contract milestones.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future catalyst development work is largely focused on optimizing catalyst composition, stability, and active site density. In situ X-ray absorption and Raman spectroscopy will provide information about catalyst composition, structure, and degradation under realistic working conditions. This information can then be used to further refine catalyst structure to optimize performance. Future durability testing and catalyst ink development will evaluate performance in full electrolyzer cells at elevated temperatures. This work will also accurately determine OER overpotentials to understand performance losses and optimization of fuel cell architecture. Additional modeling efforts will identify how the presence of specific electrolyte ions impact membrane and cell performance. Finally, full MEA optimization and testing will be conducted at NREL in fiscal year (FY) 2019.
- The project has positioned itself for completing the contractual milestones in a timely manner. The diagnostic, performance, and durability testing on the membrane and catalysts scheduled for the balance of this activity improve the data quality sufficiently for a thorough and accurate assessment of the developed technological elements.
- The proposed future work is very well aligned with ongoing efforts.

Project strengths:

- This is an excellent team with broad expertise and an approach that includes all relevant aspects in development of PGM-free electrolyzers.
- This project is successfully developing high-performing, precious-metal-free HER and OER catalysts for hydrogen production in MEA electrolyzers. This approach is key for realizing cost-effective and sustainable hydrogen generation. The project has many parts, but it has demonstrated good collaboration and has a high chance for success.
- The team is well-connected and understands where to collaborate to get either the knowledge or the analysis required to further the work.

Project weaknesses:

- This is a very strong project.
- No weaknesses were found.
- Requiring that source water be doped as an anolyte will likely add challenges to the system that is eventually deployed.

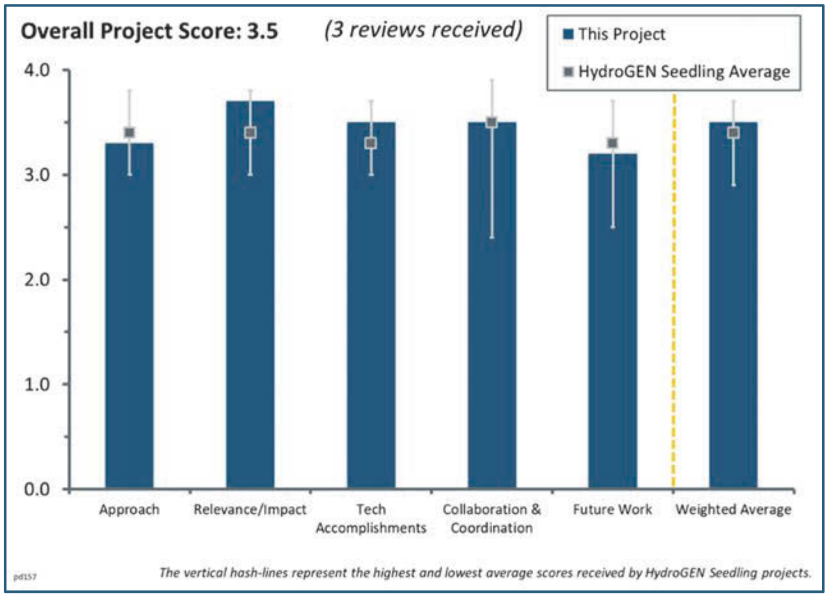
Recommendations for additions/deletions to project scope:

- It would likely be worthwhile to peruse the expanding EMN and HydroGEN data hub prior to executing FY 2019 activities. There is potentially some relevant data that already exists, which would enable this activity to advantageously redirect resources.
- The project scope is appropriate.
- The team should better delineate contributions among the participants.

Project #PD-157: Platinum-Group-Metal-Free Oxygen Evolution Reaction Catalysts for Polymer Electrolyte Membrane Electrolyzer

Di-Jia Liu; Argonne National Laboratory

Brief Summary of Project:



The objective of this project is to lower the capital cost of polymer electrolyte membrane (PEM) electrolyzers by developing low-cost, platinum-group-metal-free (PGM-free) oxygen evolution reaction (OER) electrocatalysts. The project is developing high-activity, high-conductivity, durable metal–organic framework (MOF)-based catalysts via both direct (e.g., solvothermal) and template (e.g., infiltration) synthesis approaches with one, two, or three transition metals. The most promising MOF-based catalysts will then be incorporated in a 3-D porous nano-network electrode (PNNE) architecture. The goal is to produce durable PGM-free OER catalysts with performance approaching that of current Ir-based PGM catalysts. Argonne National Laboratory (ANL) is partnered with Giner, Inc., and University at Buffalo (UB) and is leveraging national laboratories within the HydroGEN consortium.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- This project will attempt to reduce hydrogen evolution costs by creating high-activity, PGM-free OER catalysts that can operate in acidic conditions. PGM-free OER catalysts composed of first-row transition metals (Ni, Co, Fe) have shown great promise in alkaline OER applications. However, these materials typically demonstrate severe instability in acidic conditions. This project uses metal–organic frameworks (MOFs) and zeolitic–imidazolate frameworks (ZIFs) containing mixtures of Fe, Co, Ni, and Mn to promote the OER in an acidic electrolyte. A variety of metal mixtures will be screened to determine the optimum composition. Current results show decent activity and remarkable stability for transition metals in acidic conditions. The project leverages Energy Materials Network nodes via computational modeling at Lawrence Livermore National Laboratory (LLNL) and Lawrence Berkeley National Laboratory (LBNL), electron microscopy at Sandia National Laboratories (SNL), and electrode optimization and catalyst characterization at National Renewable Energy Laboratory (NREL). Finally, the project partners with Giner, Inc., an industrial partner specializing in water electrolyzer technology. This is a well-rounded project with a good approach.
- This project has focused all of the team's efforts onto one problem (PGM-free OER catalysts) and has methodically evaluated a number of potential options. The only recommendation would be to move the migration from the rotating disk electrode (RDE) to the membrane earlier in the process.
- The approach for improving activity and durability is excellent. However, it is not clear how the project plans to reduce the cost of the OER catalyst to less than 1/20 of the cost of the Ir catalyst, which is the primary goal of the project.

Question 2: Relevance/potential impact

This project was rated **3.7** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The ability to generate a cost-effective and high-performing MOF-based, PGM-free catalyst would both reduce the cost of electrolyzers and expand the deployment to support distributed hydrogen generation. It would also mitigate any supply issues associated with a PGM-based catalyst.
- The project is relevant to the HydroGEN consortium's mission of developing low-cost, high-activity catalysts for water-splitting technologies. This project will directly address this mission by developing low-cost, high-activity transition metal catalysts for the anodic OER in acidic conditions.
- This project is essential to the overall DOE Hydrogen and Fuel Cells Program goals of reducing the cost of production. However, the lead researchers should consider quantifying and demonstrating the cost advantage of at least one of the materials under study, say, the Co-MOF- or Fe-ZIF-based catalyst, over conventional PGM catalysts.

Question 3: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The project has demonstrated good progress to date by successfully completing two performance milestones and is 50% complete on a third. These milestones include the synthesis of nine new ZIF-based catalysts and two MOF-based OER catalysts. These catalysts show activity comparable to other literature examples of PGM-free OER catalysts and are approaching the performance of industry-standard Ir-black. Moreover, a Co-MOF OER catalyst shows much lower degradation compared to Ir. The project team is very close to meeting the go/no-go milestone of demonstrating a PGM-free OER catalyst with an overpotential <350 mV or 15 mV higher than Ir-black at 10 mA/cm^2 in an acidic electrolyte.
- The project team has demonstrated multiple PGM-free catalysts from different partners, with reasonable performance on a RDE with a very low pH electrolyte. The team is currently setting up to migrate from RDE testing to PEM testing.
- The results from the activity and durability test of the ANL catalyst in an acidic environment, compared to a conventional PGM-based catalyst, look encouraging.

Question 4: Collaboration effectiveness

This project was rated **3.5** for its collaboration and coordination with HydroGEN and other research entities.

- The project has so far shown good collaboration with HydroGEN consortium capabilities. The project includes modeling efforts from LLNL and LBNL, the advanced electron microscopy of catalyst materials from SNL, and catalyst testing from NREL. NREL will also support catalyst characterization and high-throughput electrode optimization to maximize catalyst performance. Ongoing modeling at LBNL and LLNL will provide realistic structural models to improve understanding of catalyst performance.
- This project includes federal laboratories, commercial vendors, and partners from academia. Participants work toward their strengths within a logical and methodical plan. Specific procedures are identified to submit results to the HydroGEN consortium.
- This project has good collaboration with NREL on establishing baseline activity and durability testing. The computational modeling collaboration with LLNL and LBNL, as well as the transmission electron microscopy (TEM) work with SNL, also look fine, although the impact or link of those results to observed activity or durability data is lacking.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work is centered on improving the performance and durability of Co- and Fe-based MOF catalysts via compositional control (doping), as well as improving the design of PNNEs through an electrospinning deposition technique. The optimized catalysts will be incorporated into the membrane electrode assembly (MEA) and tested by Giner, Inc., to achieve the go/no-go milestone criteria. This future work is appropriate.
- The work plan is logical and focused on the stated goal of reducing the cost of PEM electrolyzer catalysts. The eventual testing of the PGM-free catalysts in a PEM MEA will reveal any stability or performance issues.
- The proposed work on MEA fabrication and PEM electrolyzer testing with Giner, Inc., is a logical next step. The continued development of MOF-based OER catalysts by both ANL and UB also makes sense. However, it is curious that the future plan does not include any work on ZIFs. It is unclear whether this is an oversight or the project team has decided to abandon ZIF-based catalysts, despite claims that the "UB team is making excellent progresses [sic] in activity and durability improvements for FeMx-ZIF-8 and FeMx-ZIF-8/Oxide-based catalysts." Also, if the performance tests on activity and durability of the current OER materials are acceptable, it is unclear why the team would start a new synthesis method with graphene, atomic layer deposition, etc., rather than just continue to improve on the current method.

Project strengths:

- The project has shown impressive performance and stability for PGM-free OERs in acidic media. The catalysts are very stable and are approaching the performance of state-of-the-art Ir-based catalysts.
- This project concentrates resources to address a single problem: the rate-limiting OER. There is no evidence of resource dilution on tangential activities.
- At this point, the project strength is perhaps the synthesis and testing of the PGM-free OER catalysts.

Project weaknesses:

- The slow progression from RDE to MEA may slow the down-selection process for catalysts within the activity, thereby potentially consuming resources that could be devoted to other activities.
- The project lacks a direct link to catalyst performance, although the goal is to reduce cost by 5%.

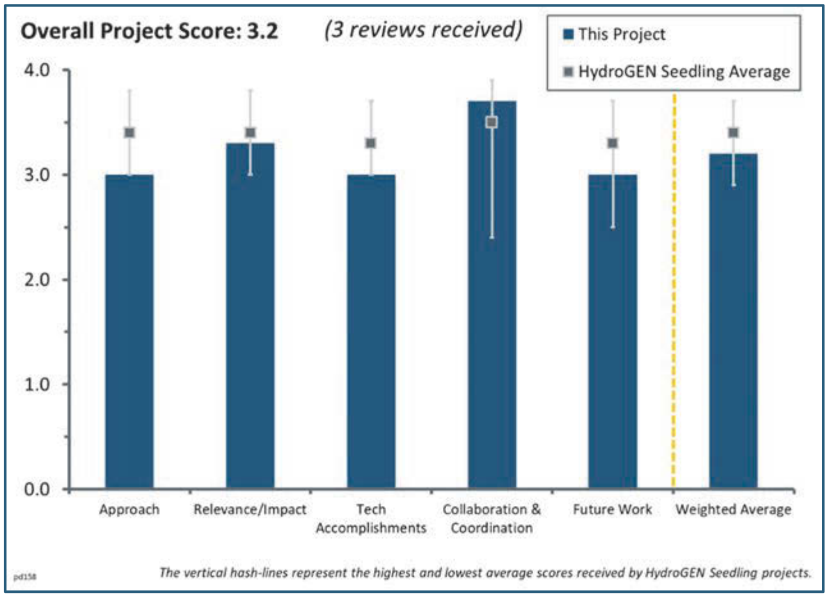
Recommendations for additions/deletions to project scope:

- There are no modifications to recommend.
- The project scope is appropriate.
- The lead researchers should consider quantifying and demonstrating the cost advantage of at least one of the materials under study, say, the Co-MOF- or Fe-ZIF-based catalyst, over PGM catalysts.

Project #PD-158: High-Performance Ultralow-Cost Non-Precious-Metal Catalyst System for Anion-Exchange Membrane Electrolyzer

Hoon Chung; Los Alamos National Laboratory

Brief Summary of Project:



The primary objective of this project is to develop low-cost, active, and durable platinum-group-metal-free (PGM-free) oxygen evolution reaction (OER) and hydrogen evolution reaction (HER) catalysts with high performance in an anion-exchange membrane (AEM) water electrolyzer. The HER and OER catalysts being developed are based on Ni-La alloys and $LaSrCoO_3$ (LSC)-based perovskite materials, respectively. The catalysts and electrodes will be carbon-free, and a pure water feedstock (i.e., no added electrolyte) is targeted. In addition to utilizing HydroGEN consortium national laboratory capabilities, the project team will partner with Pajarito Powder, LLC, for catalyst scale-up activities.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The project team is developing PGM-free OER catalysts from $LaSrCoO_3$ (LSC)-based materials for operation in alkaline water electrolysis systems. The approach involves using anion exchange membranes in conjunction with an organic cation (butyltrimethylammonium [BTMA+]) in the electrolyte to promote the OER in perovskite-based catalysts. These PGM-free catalysts are projected to eliminate the performance degradation associated with the organic components of the membrane, which can poison the active sites of traditional precious-metal catalysts. Understanding the interfacial phenomena that occur at the catalyst–membrane–electrolyte will help improve OER systems.
- In an attempt to simplify the overall system, the project team addresses the alkaline electrolysis cell as a whole to avoid the complications with recirculating an alkaline solution. This guided development of the membrane, the ionomer, and both HER and OER catalysts leads toward a low-cost integrated system. It would be helpful to identify the source of the contaminating benzene that would compromise the catalyst.
- The approach is based on the utilization of perovskite materials and Ni-La alloys in alkaline electrolyzers. This is not a novel or original idea; however, it is worth exploring in this applied project.

Question 2: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The project is relevant to the HydroGEN consortium's mission to develop cost-effective, precious-metal-free catalysts for hydrogen production. Since OER is a major energy component of water splitting, the identification of robust, PGM-free catalysts with improved stability will directly achieve these goals. The elimination of PGM-based catalysts will also allow for the use of cheaper components and hydrocarbon-based membranes. The expected roughly 50% reduction in stack costs will help obtain the target of <$2/kg H_2.

- This project has the potential to eliminate the recirculating electrolyte to simplify the overall system, minimize carbon in the membrane electrode assembly (MEA) to improve longevity, and utilize PGM-free catalysts to decrease cost and increase the number of deployable systems to improve the chances of achieving the DOE target metrics.
- The potential impact to DOE goals might be significant if this project delivers all projected milestones.

Question 3: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The project has shown good progress; the team has completed fiscal year 2018 first- and second-quarter (Q1 and Q2) milestones involving the establishment of catalyst synthesis equipment, the synthesis of HER and OER catalysts, and the setup of the alkaline electrolyzer testing station. Q3 and Q4 milestones are on track, including the go/no-go performance criteria. The current data shows improved durability and has comparable activity to a state-of-the-art IrO_2 OER catalyst. Six perovskite OER catalysts have been compared with IrO_2 in both 0.1 M KOH electrolyte and 0.1 M BTMAOH electrolyte. The perovskite catalyst showed slightly reduced OER activity in 0.1 M KOH but had better performance. The perovskite catalysts showed greatly improved performance in 0.1 M BTMAOH compared with IrO_2.
- In the first year of funding, this project made significant progress in the establishment of synthesis equipment for both OER and HER catalysts, as well as in the AEM system setup. The first-year milestones and go/no-go decision are expected to be met and possibly exceeded; the project is predicted to result in significant AEM water electrolysis technology progress.
- By and large, the test data and progress are solid and illustrate that the activity is on track to continue with success. The notable exception, however, is the durability data. In the end application, an electrolyzer will likely be generating hydrogen for extended periods of time over a range of production rates. From that perspective, the cycle data well illustrates one aspect of durability: cycle life. The data generated by an hour-long steady-state test dubiously represents the other element of durability: stability. This is a fundamental research project, so accumulating hundreds or thousands of hours is neither feasible nor practical. It should be feasible, however, to demonstrate catalyst stability for more than an hour.

Question 4: Collaboration effectiveness

This project was rated **3.7** for its collaboration and coordination with HydroGEN and other research entities.

- The project effectively leverages four nodes. For example, the density functional theory and ab initio calculations node at Lawrence Berkeley National Laboratory provides computational input for the catalyst design and synthesis; the node also helps provide atomic-level details on catalyst reactivity. Initial results have predicted a much stronger binding of BMTA+ at IrO_2, compared with the LSC perovskite. The surface analysis cluster node at the National Renewable Energy Laboratory (NREL) provided X-ray characterization of catalysts. Separators for the hydrogen production node at Sandia National Laboratories supplied state-of-the-art alkaline membranes and ionomers. Hydrogen in situ test capabilities for the hydrogen production node at NREL provided the project with MEA fabrication and an in situ electrolyzer test. These tests have produced initial performance data that shows improved perovskite-S performance compared with IrO_2 at potentials greater than 1.7 V.
- With four government laboratories and a commercial vendor progressing toward an affordable system, it would be challenging to identify a better example of the integrated teamwork envisioned by the HydroGEN consortium.
- This project consists of excellent coordination between the participants.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future efforts are reasonable; the planned work includes the study of the impact of other organic alkaline electrolytes, such as TMAOH, and the study of their impact on rotary disk electrode HER/OER with PMG-free catalysts. The planned experiments will probe phenomena occurring at the PMG-free catalyst and anion-exchange ionomer membrane, including in situ X-ray absorption spectroscopy (XAS). This fundamental information will lead to improved catalyst design for testing in AEM water electrolyzer tests. The project partner, Pajarito Power, will scale catalyst synthesis into the 25 g/batch range.
- With the progress made to date, the integrated alkaline electrolysis system testing at the suite of national laboratories will provide valuable results that should guide further design efforts and inform the balance of the HydroGEN consortium.
- The proposed future work is well aligned with ongoing efforts.

Project strengths:

- The project team has effectively synthesized a series of PGM-free, perovskite-based OER catalysts that show comparable performance to state-of-the-art IrO_2. The team has also shown the impact of organic alkaline electrolytes on OER performance. Incorporating these concepts into working systems will ultimately provide a route to high-activity and low-cost water-splitting technology.
- The team uses perspective from the end application to guide the project. This reduces the risk of developing an architecture that requires excessively complex and expensive deployed systems. This project also successfully leverages the capabilities of multiple partners.
- The project is well focused and well executed, with clearly defined milestones and objectives. It seems that all projected targets in the first year will be met.

Project weaknesses:

- There are notable schedule pressures on the project participants. The brevity of the presented catalyst stability data renders this one data set dubiously relevant.
- Not much work other than prolonged cycling is being done for careful durability studies.
- The overall performance does not appear as high as other PGM-free catalysts.

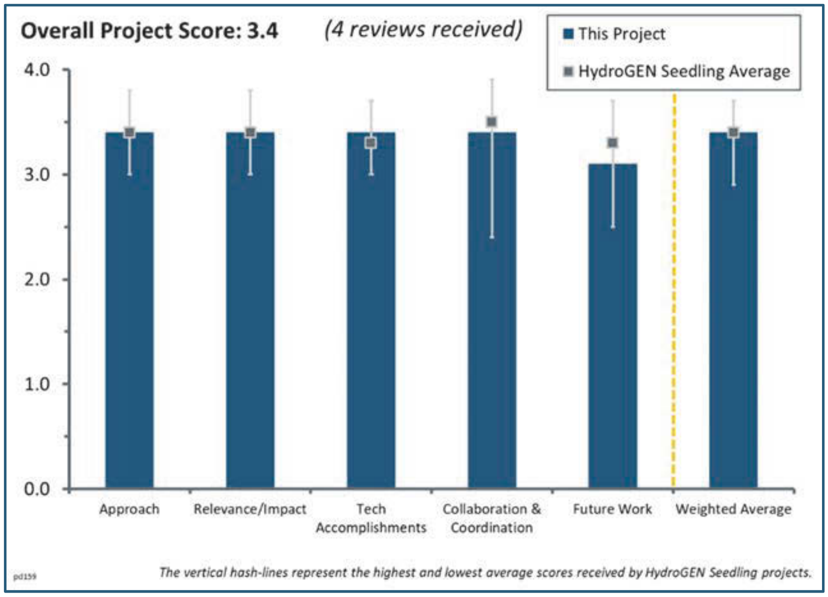
Recommendations for additions/deletions to project scope:

- It is recommended that the team include catalyst stability data of at least tens of hours. It would likely be worthwhile to peruse the expanding Energy Materials Network and HydroGEN consortium data hub prior to executing second-year activities. There is a potential that some relevant data already exists, which would enable this activity to redirect resources to the team’s advantage.
- In situ durability evaluations should be performed on PGM-free catalysts, such as inductively coupled plasma mass spectrometry (ICP-MS).
- It is recommended that the team form a better description of the proposed future work and define a clearer path toward catalyst optimization.

Project PD-159: Scalable Elastomeric Membranes for Alkaline Water Electrolysis

Yu Seung Kim; Los Alamos National Laboratory

Brief Summary of Project:



The objective of this project is to develop stable, high-performance, and economically affordable alkaline anion-exchange membranes for water electrolysis operation. A low-cost synthetic method based on acid-catalyzed condensation reaction (Friedel–Crafts alkylation) will be developed to fabricate the styrene-based triblock copolymers based on polystyrene-b-poly(ethylene-co-butylene)-b-polystyrene (SEBS) to replace the prohibitively expensive metal-catalyzed reaction route. The project team, which also includes Rensselaer Polytechnic Institute and Proton OnSite, aims to develop economically viable elastomeric ionomers having conductivity at least equivalent to polyaromatic electrolytes, with much-improved mechanical properties.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- This project will develop economically viable alkaline-conducting materials and demonstrate their performance in alkaline water electrolyzer systems. This is a good approach because membrane durability and performance has direct impacts on overall catalytic water splitting. Poor membrane performance and/or degradation will hinder the performance of even the best catalyst, so this is an important aspect to achieving low-cost hydrogen production from water splitting. The approach is reasonable for the one-year performance period and project cost. Key barriers to membrane performance include alkaline stability, hydroxide conductivity, and mechanical properties. The team has previously demonstrated more than 2000 hours of operation in an alkaline electolyzer using polyaromatic electrolytes. This work aims to develop cheaper, more mechanically robust elastomeric isomer materials with equivalent performance.
- This project focuses all effort onto one problem (alkaline membrane applicability) and methodically evaluates a number of potential options. The inclusion of both the catalyst–ionomer interface and the ionomer–membrane interface increases the potential for a successful outcome.
- This project's straightforward approach benefits from an Energy Materials Network (EMN) node, as well as academic and industrial partners.
- Lowering the cost of alkaline electrolyzer materials is a primary goal for the project. However, it is not obvious why or how the new membrane materials or synthesis approach is expected to be less expensive. It is unclear whether the absence of a platinum-group-metal (PGM) catalyst alone makes the materials affordable or if there will be a need for other improvements. The project needs to describe the approaches on how to achieve lower cost.

Question 2: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- Membrane stability and performance are crucial components of electrolyzer performance. Improving state-of-the-art performance metrics, including hydroxide conductivity, stability, and mechanical robustness, is key to realizing cost-effective hydrogen production devices. This project directly addresses these issues. Better membrane performance will lower capital cost by removing the high noble metal loading requirements. It will also allow use of less expensive cell components because of alkaline conditions. Less permeation across the membrane will allow operation at higher pressures and current densities. Success will help mature alkaline membrane-based water electrolysis technology and ultimately achieve the goal of $2/kg H_2.
- Leveraging the polymeric tuning from previous work has resulted in a series of viable membrane options for continued development. The project is on schedule and pursues the path forward with a high probability of success.
- Exploring and demonstrating a stable and low-cost alkaline hydroxide conducting material is fully aligned with the EMN's low-temperature electrolysis development goals.
- This effort has the potential to lead to significant cost reduction of hydrogen production.

Question 3: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and DOE goals.

- The project has successfully synthesized and characterized semi-crystalline and cross-linked SEBS membranes. The membranes show good hydroxide (OH^-) conductivity and excellent stability during a 500-hour test in 1 M NaOH at 80ºC. First- and second-quarter (Q1 and Q2) milestones have been met, and Q3 and Q4 milestones are 50% or greater toward completion. Three materials have met the go/no-go decision criteria. Future testing will validate the performance of additional membrane materials. Modeling electrolysis performance based on membrane properties has been initiated. The findings predict thinner, more conductive membranes will improve overall cell performance. X-ray scattering experiments have characterized the membrane crystallinity as a function of water uptake. These results will help guide membrane optimization for improved performance and mechanical strength.
- Leveraging the polymeric tuning from previous work has resulted in a series of viable membrane options for continued development. The project is on schedule and pursues the path forward with a high probability of success.
- The project has met all milestones to date.
- The conclusion that "[Alkaline exchange membrane] properties are controlled by [ion-exchange capacity] and tailoring chemical structure" is not supported by the data presented. It is suggested that the project team further explore the causes or reaction mechanisms. For example, the team should determine whether there is a correlation between water uptake and hydroxyl conductivity, at least for some of the materials.

Question 4: Collaboration effectiveness

This project was rated **3.4** for its collaboration and coordination with HydroGEN and other research entities.

- The project shows good collaboration and coordination with other institutions. For example, the project has leveraged the modeling and electrochemical characterization node, while future efforts will utilize roll-to-roll manufacturing, hydrogen generation and dispensing, and X-ray scattering nodes. The project will also partner with Proton Onsite to demonstrate the best performance and durability of alkaline electrolyzer in the second and third years. Los Alamos National Laboratory (LANL) has worked closely with Sandia National Laboratories to improve chemical stability of benchmark anion-exchange membranes. LANL has discussed a possible collaboration with the National Renewable Energy Laboratory team for testing membrane-based water electrolyzers.

- This activity has delivered a potentially viable membrane for use in an alkaline system. This suggests the inclusion of the correct participants collaborating at an appropriate level to succeed.
- The collaborative plan among materials discovery, verification, and characterization teams looks sound.
- There are good interactions with the synthesis team and EMN nodes.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Future work includes optimization of membrane chemical structures to balance OH- conductivity and mechanical durability, as well as completion of stability testing. The project will down-select alkaline ionomer materials based on micro-electrode testing and in situ area-specific resistance measurement and stability testing in electrolyzer cells. Future work with Proton Onsite will validate membrane performance in electrolyzer cells and test real-world stability.
- This is a good plan to address critical issues.
- The integration of the cross-linked alkaline-exchange membrane polymer will not be integrated into an electrolyzer for evaluation in a completed membrane electrode assembly until the second fiscal year. Until then, the component fundamental properties will be characterized, and a more durable balance between ion-exchange capacity and polymer durability will be sought.
- The proposed future work (assumed through September 30, 2018) to optimize the chemical structures is a bit vague. Some specific measures on how to achieve this would be helpful.

Project strengths:

- Empirical data suggests a viable alkaline membrane with potential for refinement to improve durability. The team has demonstrated the capability of executing this refinement.
- Controlled synthesis of modified SEBS polymers is the major strength.
- The novel lower-cost membrane synthesis approach is a project strength.
- The project scope is well defined and appropriate.

Project weaknesses:

- No substantial weaknesses have been observed.
- Lack of mechanistic discussion of the new materials' property–performance relationship is a weakness.
- The first year's work could have had more collaboration with EMN nodes.

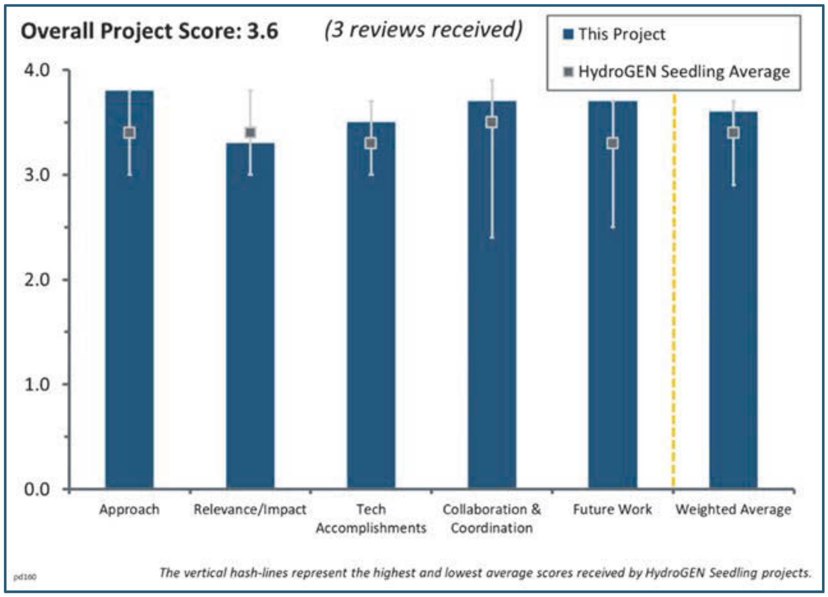
Recommendations for additions/deletions to project scope:

- The project scope is well defined and appropriate. Future work proposes adequate collaboration with EMN nodes.
- It would likely be worthwhile to peruse the expanding EMN and HydroGEN data hub. There exists the potential that some relevant data already exists that would enable this activity to advantageously redirect resources.
- It is recommended that the project team provide some explanation of why and how the new membrane materials or synthesis approach is expected to be less expensive than M-Cat or base materials.

Project #PD-160: Best-in-Class Platinum-Group-Metal-Free Catalyst Integrated Tandem Junction Photoelectrochemical Water-Splitting Devices

Charles Dismukes; Rutgers University

Brief Summary of Project:



This project will identify the best technical approaches to fabricate both high-performance (HP) and high-value (HV) platinum-group-metal-free (PGM-free) catalysts for photoelectrochemical (PEC) cells without compromising system efficiency. Next-generation devices must eliminate PGMs, even though they perform well, because of cost and sustainability limitations. Using recently developed low-cost HP catalysts, the team will examine the optimal pairing of these materials with established HP and emerging HV photoabsorbers. Cost–benefit analysis of full HP and HV devices and their individual components will enable the preparation of a hybrid product that will significantly advance the state of the art and that has the potential to deliver on all U.S. Department of Energy figures of merit: cost, performance, and stability.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The project approach is very strong. The team clearly identified relevant barriers related to substituting PGM catalysts with earth-abundant materials that perform at the same level for solar water-splitting purposes. Other barriers related to catalyst light absorption and protection semiconductor components were identified. The research proposed is well aligned with the project objectives and is likely to result in advances toward surpassing the barriers identified. The project is well integrated with HydroGEN partners at the National Renewable Energy Laboratory (NREL), who will provide both HP III-V light absorbers and $ZnSnN_2$ HV materials. The interactions with HydroGEN partners effectively complement the expertise of the Rutgers University lead investigators in electrocatalysis.
- The team is specializing in non-PGM oxidation evolution reaction (OER) and hydrogen evolution reaction (HER) catalysts that are competitive with PGM catalysts. This is a worthy goal. The team is partnered with experts within the HydroGEN consortium, which will allow the project catalysts to be tested with the best-performing PEC materials. This project also takes a look at using these catalysts in conjunction with less expensive PEC materials to develop a HV PEC device. The approach looks likely to be very fruitful.
- The approach seems appropriate. The milestones are pretty nice. It seems as though the project team expects to meet or exceed all milestones. The team should consider the use of stretch milestones in future project phases. The purpose of these types of milestones is to give the project team an opportunity to demonstrate outstanding performance if they are achieved. If, however, the team fails to achieve a stretch milestone, the project is not punished. This is an effective way to internally standardize what the project team thinks is a big advancement versus what advancements may be expected as a matter of course.

Question 2: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The project supports, in part, progress toward the goals of the Hydrogen and Fuel Cells Program in several ways. First, the development of inexpensive electrocatalysts could lead to lower costs when compared to state-of-the-art PGM materials, but these cost reductions are not likely to be significant enough to reach the $2/kg goal. The fraction of the cost that the electrocatalyst accounts for is small compared to other factors (e.g., efficiency and lifetime), and thus the team's focus on high-efficiency catalysts is appropriate. Implementing III-V semiconductor components could lead to the required efficiencies to achieve the desired hydrogen production cost, but these technologies suffer from significant cost drawbacks. The interactions with the NREL team are also very appropriate, as advances in III-V fabrication could help alleviate these cost disadvantages. Also, the incorporation of research on HV semiconductors is relevant, as it can also help achieve the target cost goal—as long as high efficiency is proven.
- This project supports the development of non-PGM and scalable electrocatalysts for PEC water splitting. It will lower hydrogen costs by increasing solar-to-hydrogen (STH) efficiency, decreasing production costs using lower-cost materials, and increasing lifetime. These are important to achieving the DOE target of hydrogen for <$2/kg.
- The performance is held relative to a standard. The cost tornado plot seems to suggest fairly equal opportunity for reducing costs from the center point versus getting stuck with a cost that is higher than the central point. This perhaps has better odds or opportunity than in other projects, improving the relevance and the chance for this project to stay afloat.

Question 3: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The project has made significant progress toward meeting the intended performance indicators. Two milestones have been achieved related to the performance and stability of the $LiCoO_2$ OER electrocatalyst and the development of a high-efficiency III-V/Ni_5P_4 photocathode. The team has also made significant progress toward the first go/no-go criteria, and although the team has not achieved the desired current density to date, the demonstrated photocathode stability at roughly 90h at >8 mA/cm^2 is very promising. This stable behavior was achieved through the protection of the semiconductor with TiN, which protects the light absorber during the fabrication of the Ni_5P_4 layer. It is unclear whether higher current efficiencies (and STH efficiencies) will be possible with the materials system chosen, or what the strategy to improve performance is. One significant challenge is avoiding significant light losses in the electrocatalyst layer.
- Developing high-quality HERs and OERs that are stable and competitive with PGM catalysts is impressive. The team looks to be meeting project milestones and has the data to back it up.
- The accomplishments have been good. The team is advised to watch out for the oxides in the nickel phosphide film. It is unclear whether the occurrence of oxygen atoms is spatially correlated with the occurrence of Ni and/or P, and whether any spectroscopic evidence exists to justify invoking oxides in deconvolution in the x-ray photoelectron spectroscopy (XPS) spectra.

Question 4: Collaboration effectiveness

This project was rated **3.7** for its collaboration and coordination with HydroGEN and other research entities.

- The collaboration between the lead researchers and the HydroGEN Energy Materials Network has been very effective, as evidenced from successful early results achieved through joint efforts between Rutgers University and NREL.
- Good-to-excellent collaboration exists.
- The team is making good use of the expertise in the HydroGEN consortium for synthesis and benchmarking. It is unclear how the high-throughput/combinatorial synthesis node was used, other than for the fabrication of the $ZnSnN_2$, or whether the high-throughput synthesis was used to discover this material.

Question 5: Proposed future work

This project was rated **3.7** for its proposed future work.

- The proposed future work slide is perhaps the best that this reviewer has seen. It provides enough detail to shine light on the scientific line of reasoning that justifies the work, and it includes some SMiles ARbitrary Target Specification (SMARTS) characters.
- The proposed future work is consistent with the needs of the project to achieve the intended goals. Thrust 1 future work is heavily focused on stability performance, which is reasonable given the potential impact on hydrogen cost, but additional work on performance improvements will also be needed to achieve the DOE goals. More significant challenges are faced in Thrust 2, in which the HV PEC materials exhibit significant drawbacks, in terms of performance and stability. The proposed activities are reasonable efforts to improve the potential of HV materials.
- The proposed work addresses the remaining barriers. Importantly, a large focus is placed on increasing the stability in alkali conditions; this will be tested under diurnal cycles.

Project strengths:

- The strengths of the project include the following:
    - The electrocatalysts developed for the team (both for OER and HER) show very promising performances that are comparable to PGM catalysts.
    - The protection strategies have allowed the team to demonstrate enhanced stability.
    - The research approach is well designed for the project needs, and the team has been able to achieve the initial project milestones.
    - There are excellent interactions between team members and between lead researchers at Rutgers University and the HydroGEN consortium.
- The non-PGM OER and HER catalysts have performances that are on par with PGM catalysts. Another strength is the promise of TiN film for protection against corrosion.
- This project team seems technically competent and is publishing based on project results.

Project weaknesses:

- The project team should consider using stretch milestones so that one may differentiate between “business as usual” and truly remarkable advancements.
- There are two weaknesses within this project. The first is that the strategy to achieve the high performance required for PEC materials containing III-V semiconductors is unclear; light absorption losses in the electrocatalysts will be challenging to overcome. The second weakness is that the choice of HV materials is likely to result in limited performance, which would make it very difficult to achieve the $2/kg hydrogen target.

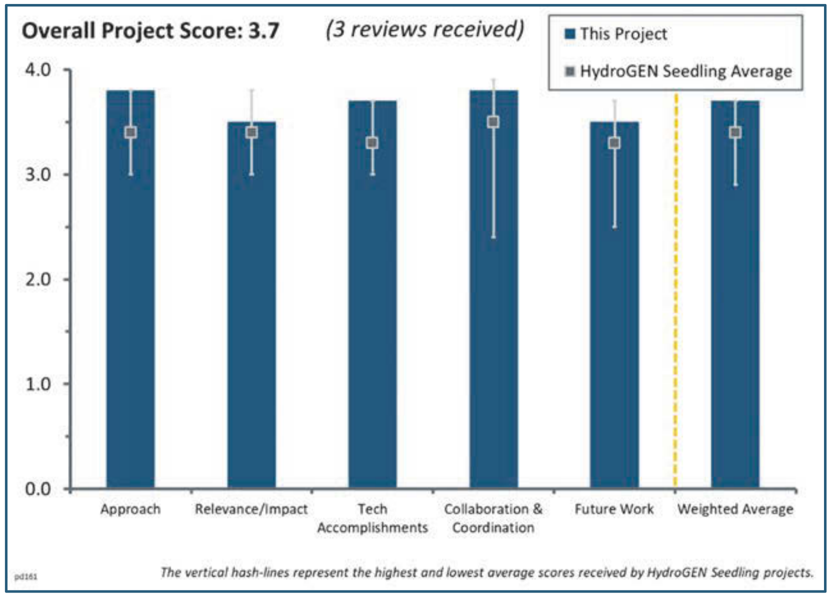
Recommendations for additions/deletions to project scope:

- Since the team has shown significant progress in the development and protection of HP III-V PEC materials, most of the benefits in the future research will likely come from advances in HV materials. Shifting efforts from Thrust I to Thrust II might make sense for the duration of the project.

Project #PD-161: Protective Catalyst Systems on III-V and Silicon-Based Semiconductors for Efficient, Durable Photoelectrochemical Water-Splitting Devices

Thomas Jaramillo; Stanford University

Brief Summary of Project:



The overall goal of this project is to develop unassisted water-splitting devices based on III-V materials, creating pathways to improve performance in terms of efficiency (>20% solar-to-hydrogen [STH]), durability (two weeks), and cost (<\$200/m^2). Two distinct water-splitting schemes are being pursued: Scheme 1 (tandem III-V/III-V) aims to develop high-efficiency devices with tandem III-V photoabsorbers (e.g., $GaInP_2$/GaInAs), and Scheme 2 (III-V/Si) targets cost reduction while maintaining high efficiency by growing InGaN on crystalline Si. Both schemes will be coupled with thin-film, semi-transparent hydrogen and oxygen evolution reaction catalytic/protection layers containing reduced or zero precious metal content that can enhance durability while maintaining high efficiency and enabling low material costs.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The research approach of this project is well designed and appropriate to achieve the goals. The barriers are clearly identified, and the team structure is composed of experts with complementary expertise that is likely to result in surpassing these barriers. Protection III-V semiconductors with electrocatalysts can lead to stable interfaces for solar water splitting, growing III-V semiconductors in Si can significantly lower the cost of production, and testing the system for long periods of time will provide insights into the possible implementation of the proposed photoelectrochemical (PEC) materials system. The activities in budget period 1 strongly support the validation of the technology being studied.
- The team identifies key barriers including stabilization, fabrication of high-quality InGaN on Si, and benchmarking on long timescales. The project proposes promising ways to overcome these barriers with the help of the National Renewable Energy Laboratory (NREL) characterization, analysis, and benchmarking nodes.
- The project seeks Si/III-V tandem solar cells to enable the technology, but the proposed target for this is a very qualitative "high-quality InGaN epitaxial growth on Si." The project claims that MoS_2 provides stability, yet the derivative of the curve representing current density versus exposure time does not equate to zero. In other words, the system is not stable in the strict sense of the word. Regarding the stabilization of Si for months using MoS_2, the J value goes to zero after about Day 65, and it does so spectacularly. It is unclear whether this is catastrophic failure and what the mechanism behind the failure is, as well as how that mechanism has been analyzed as part of a long-term strategy to overcome the failure. The technoeconomic analysis does not include error bars or other such representations of uncertainty. Uncertainty tends to compound and therefore confound the selection of winning technologies. The poster did not seem to attempt to address this. The corrosion analysis of the materials could be better structured. Metal–organic chemical vapor deposition (MOCVD) requires high vacuum. It would be beneficial to

eliminate high vacuum steps to decrease costs. Several of the project milestones contain qualitative statements or components. For example, Milestone 1.1 states, "Demonstrate >100 h stability," but "stability" is not defined as less than some absolute or less than some relative change from the starting point. Thus, if the time-based derivative of the curve representing the systems performance is not equal to zero, then the milestone is not met. Milestone 4.1 is very vague: "Demonstrate effectiveness of the operando microscopy flow cell measurement technique on a benchmark photoelectrode." This does not specify success criteria for process stability and absolute accuracy. It does, at least, specify that some benchmark will be used as a (presumably) standard material. The go/no-go states that the project will "...provide a viable pathway for achieving 20% STH efficiency..." It is unclear what this even means. "Viable" is an adjective describing the noun "pathway"; hence it would then be expected to see some pathway or timeline with SMART (specific, measurable, attainable, relevant, and time-bound) criteria flanking each and every technical point along this technology development line. It is unclear if "viable" means that no targeted performance metric should fall outside of two sigma from the existing known mean for that variable's performance. In other words, it is unknown if "viable" means that the project need not invoke any statistical long shot to achieve the overall objectives. It is unclear whether "viable" should be taken to mean that no invention must occur to achieve the objectives. Surely, pathways that must invoke invention cannot be guaranteed viable unless invention can be guaranteed. No such philosophy, schematic, analysis, or other definition of "viable" seems to be presented.

Question 2: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The project focuses on improving the efficiency and stability of high-performing PEC materials—two of the most important factors in achieving low hydrogen production costs. This focus is highly relevant for DOE's goals and could lead to substantial advances toward the $2/kg of hydrogen target. One of the drawbacks is the implementation of expensive III-V materials, another area of focus of the project. The proposed approach of growing III-V on Si has high potential to lead to lower production costs for these high-performing light absorbers. The project fits well within the HydroGEN consortium, as it effectively leverages the fabrication, characterization, and on-sun testing tools available at NREL.
- Achieving >20% efficiency and high durability while using earth-abundant materials is necessary to achieve the DOE target. This project is likely to make progress toward those goals by improving stability through protection layers.
- This project seeks to use a (roughly) seven-layer device to effect the desired water-splitting reaction. It benefits from the use of established solar-cell manufacturing technologies. However, the complexity of the construct will ultimately limit the amount of cost reduction that can be achieved. The poster states that high-efficiency, durable, low-cost photoelectrodes are required to deliver cost-effective hydrogen. In other words, all three criteria need to achieve some measure of performance extremes for the technology to be viable. This will be challenging. The figure on slide 12, in which the known research/materials space is plotted as "Demonstrated Charge Passed" on the y-axis and "Onset potential vs [reversible hydrogen electrode]" on the x-axis, would have benefitted from shading the region that represents success. This would help visually emphasize the materials being studied in this project as potentially impactful, being on the edge of or in the success region.

Question 3: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- The project demonstrated a PEC photoelectrode that achieves >10 mA/cm^2 under 1 sun illumination for longer than 100 h. The team fabricated an unassisted PEC water-splitting device with a nonprecious metal hydrogen evolution reaction catalyst that achieves STH efficiencies >5% under 1 sun illumination to provide a viable pathway for achieving 20% STH efficiency, through integration strategies of the materials and interfaces under investigation.

- The team has made very significant progress toward achieving the project goals. Two go/no-go criteria have been met to date, and several of the milestones have been hit. A MoS_2 protected GaInP photoanode was demonstrated to have an efficiency >100 h, and InGaN was successfully grown on Si. Unassisted water splitting was also demonstrated for >10 h, at current densities >10 mA/cm^2 and STH >5%.
- The team has successfully grown single-crystal pn+ -$GaInP_2$, sputtered Mo onto this, and sulfidized the surface with deadly H_2S gas. Slide 11 did not explain why the MoO_3 3d peak goes away in the before/after insert. Also, the derivative of the red curve in this figure does not appear to equate to zero, suggesting that there is some change occurring in the system. The overall conclusion on slide 11, that MoS_2 is superior to PtRu, holds true. Slide 16 fails to use basic statistics to establish the precision and make claims to the accuracy of the new in situ microscopy flow cell method.

Question 4: Collaboration effectiveness

This project was rated **3.8** for its collaboration and coordination with HydroGEN and other research entities.

- The collaboration between the team members at Stanford University and the HydroGEN nodes at NREL is very strong and has allowed the team to make significant progress toward the project goals. The skills of the team members are complementary and clearly differentiated, which has led to promising results in Year 1 of the project.
- Weekly meetings with NREL and the weekly exchange of samples show a high degree of collaboration with Energy Materials Network (EMN) nodes and partners. The team has a plan in place to incorporate the project data onto the HydroGEN data hub.
- There seems to be strong interaction with NREL.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The team has a clear research plan to achieve most of the milestones proposed in the project. Fabrication of Si/InGaN PEC material systems would be a promising step toward cost-effective solar hydrogen generators. Enhancing the STH efficiency to 20% from the achieved values might prove to be challenging, and a pathway for this improvement has not been clearly defined. The proposed in operando corrosion methods would be very useful in identifying failure mechanisms and will help avoid them in future materials systems.
- Future work addresses barriers, including strategies to boost performance and strategies to probe corrosive failure mechanisms.
- The proposed future work seems to be a logical extension of the prior budget period's work. However, portions of the proposed future work are vague (e.g., "implement protection scheme and catalyst") and do not convey how efficiency will be achieved in conducting the research activities—for example, "Boosting stability and catalysis on tandem photo-absorber systems by optimizing..." (a long string of inter-related parameters is then listed). It is unlikely that the project team will measure all possible parameter combinations. It is unclear how the team concludes that a better collection of parameters was not missed, if the outcome from the narrow slice of parameters actually tested was less than perfect. It is unclear why the team did not use a statistical design of experiments to lay out the entire process space and then develop science- and engineering-based arguments to focus in on portions of that space. A design-of-experiment would inform on the parameter combinations that are actually measured, as well as those neighbors around them that were not measured; efficiency of effort is realized in this way. The work exploring corrosion mechanisms of failure is poorly articulated and should receive intense scrutiny. The mechanism of failure is likely a compounded action of chemical and physical phenomena that may not be easily de-convoluted.

Project strengths:

- This project has a very competent chemical engineer as the principal investigator (PI). All project participants are well accomplished as individuals and in teams. The idea of using a transition metal to simultaneously protect the surface and to affect the desired chemical reaction stands to open a rich and fertile field of catalysis. Indeed, some of the most important catalysts of modern times are based upon transition metals. Also, nature offers many models for the manipulation of protons using transition metal complexes. This project also presents the opportunity to run a senior design course to get a better grasp of the "for sale," ready-for-deployment embodiment of this technology.

- There is strong collaboration between Stanford University team members and the HydroGEN consortium. There is also significant progress toward project goals, promising initial results on the protection of III-V semiconductors with MoS_2 electrocatalysts. The work plan is clearly defined and well aligned with project objectives. This research approach could lead to significant advances toward DOE goals.
- The approach is strong, with high levels of collaboration and coordination with EMN nodes.

Project weaknesses:

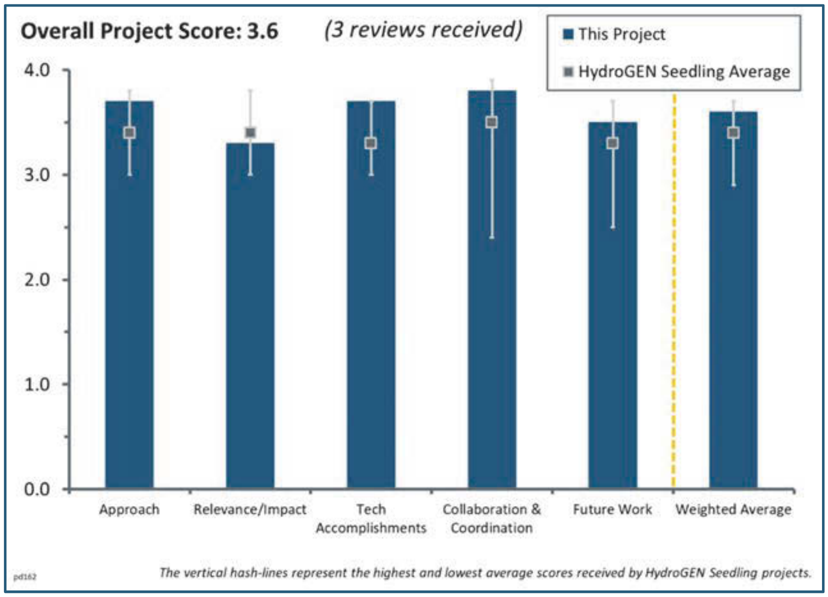
- This project needs a strong chemist if the transition metal chemistry is to be fully leveraged. Also, discussion with the PI indicated that an engineer could probably add value in devising how this technology could operate in the field.
- Significant advances are required to achieve the project's goal of 20% STH efficiency, and a clear pathway to this was not presented. Also, parasitic absorption losses in the MoS_2 may need to be investigated in further detail to avoid light losses in this layer.

Recommendations for additions/deletions to project scope:

- No additional recommendations are provided.

Project #PD-162: Novel Chalcopyrites For Advanced Photoelectrochemical Water Splitting

Nicolas Gaillard; University of Hawaii



Brief Summary of Project:

The overarching goal of this project is to create a chalcopyrite-based, semi-monolithic, tandem hybrid photoelectrode device prototype that can operate for at least 1,000 hours with solar-to-hydrogen (STH) efficiency >10%. The performance of previously identified wide-bandgap chalcopyrite materials will be improved through alkali doping to passivate $CIGS_2$ defects, and next-generation chalcopyrites (e.g., Ga-free) will be developed. The photoelectrochemical (PEC)–electrolyte interface energetics and stability will be improved by investigating alternative buffer materials and protective layers. Also, novel fabrication methods will be developed for creating the semi-monolithic chalcopyrite-based tandem devices.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The research approach is well defined and aligned with the goals of the project. The team will synthesize chalcopyrite materials with appropriate bandgaps using inexpensive printing methods. The researchers will also develop interfacial materials to protect the semiconductor components and enhance efficiency toward the solar water-splitting process. Lastly, the researchers will integrate materials in PEC configurations using conductive composite materials. The project effectively leverages several nodes of the HydroGEN consortium for its theory components, interfacial electrode protection, and PEC testing.
- The approach of the project is focused on overcoming the chalcopyrite manufacturing cost, non-ideal surface energetics, chalcopyrite durability, and device configuration. The project partners with theory, PEC benchmarking, and solid-state interface experts.
- This project seeks to integrate several technical thrusts. The organizing structure by which these coalesce needs to be better defined. The project would benefit from stating the critical path (in the technological sense). There does appear to be ownership of individual nodules of effort in which existing infrastructure and capabilities make this a natural phenomenon. For example, it is clear why the National Renewable Energy Laboratory owns that part which it owns, and it is clear why Stanford University owns that part which it owns. However, it could be clearer what exactly each is putting forth into the backbone of the technology's advancement.

Question 2: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- Developing high-efficiency, stable, and inexpensive PEC materials is central to achieving the DOE's cost target for hydrogen production. The team has clearly identified a pathway for the synthesis of tandem chalcopyrite light absorbers with tunable bandgaps, through the implementation of an inexpensive printing method. The use of this fabrication method has potential to lower the cost of hydrogen production, and the ability to stack multiple layers of chalcopyrite materials with synergistic light absorption properties could lead to higher performance. Despite this promising approach, the target efficiencies are well below the ones needed to achieve the DOE cost target. The project effectively leverages several nodes of the HydroGEN consortium for its theory components, interfacial electrode protection, and PEC testing.

- Overcoming the identified barriers is likely to make significant progress toward DOE's hydrogen production cost goals. The project makes good use of the Energy Materials Network (EMN) nodes.
- The project is doing a great job leveraging the Hydrogen and Fuel Cells Program's (the Program's) infrastructure. The science seems sound, and innovation is occurring on multiple fronts. There is some doubt as to the technology's ability to achieve the Program's cost targets. Low-cost flex-film photovoltaic (PV) manufacture has not achieved scale. Also, the project seeks to pass through a nine-layer intermediate prototype and then seeks to converge upon a six-layer device as the final goal. The approach will require semiconductor fab-type processing. The number of layers translates to a number of steps greater than or equal to this number of layers; each (or many) of these steps occur in a highly controlled, high-cost facility. This ultimately translates to a high-cost product. The cost sensitivity analysis does well to employ a tornado-type plot; however, what these plots reveal is that cost-reduction opportunity is actually skewed against us. That is to say, the size of the cost bands on the detrimental side of the indicated starting point are much larger than the size of the cost bands on the beneficial side. In other words, when it comes to cost reduction, there is more ground to lose than there is to gain. This asymmetry in the tornado plots probably becomes common for technologies that are reaching maturity. This technology has not reached maturity, and so a second interpretation is that achieving the cost targets is a long shot. The principal investigator (PI) seems to admit to this, stating that cost targets may only be met by achieving two extreme value events in concert: 25% STH and 10-year lifetime. The probability of this seems quite low.

Question 3: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- Milestones are being met, and future milestones are well on their way to being met. Efficient chalcopyrite films have been successfully printed and characterized, protection against photocorrosion with TiO_2/MoS_2 has increased the stability up to 350 hours, and innovations in transparent conductive binders have been developed to enable chalcopyrite device development. Supporting data is provided, including data from EMN nodes and partners.
- The team has shown significant progress toward achieving the proposed milestones, demonstrating the synthesis of polycrystalline chalcopyrite films and a robust nanowire-based method to create transparent binders between different PEC layers. A chalcopyrite PV device has been demonstrated with efficiency of 8.4% solar-to-electricity, placing the project close to achieving the first go/no-go criteria. Significant challenges were encountered to protect the materials under acidic conditions, but the materials seem to be stable under neutral pH.
- The PI states that the project is on track to achieve all of its milestones. This is a good outcome if the milestones were more challenging and the definition of having "met" them was less ambiguous. It may be worthwhile to consider incorporating one or more "stretch milestones," wherein the PI could demonstrate outstanding achievement if this milestone is met yet not be penalized if it is not met. This method of challenge brings into sharp contrast what is challenging for the team and what is easily met. This will vary from project to project. The milestones do appear to be Specific, Measurable, Achievable, Relevant, and Timely (SMART). The level of sophistication in how success is demonstrated could be increased. For example, there does not appear to be a widespread use of figures of merit. These mathematical formulations of success typically incorporate competing physical phenomena so as to respect the trade-offs usually encountered in developing a technology. The raw data for analyzing, to this end, are presented in the accomplishments section; it is just the synthesis of this data that could be improved upon, at least from a project management perspective. Depositing layers using a printing process instead of a vacuum process could be a big win for reducing manufacturing costs. The data show that impurity levels need to be better controlled, though, and this could re-introduce costs. When a new process is introduced, there must come a time when the stability of the process and the reproducibility of the process must be established. The

argument is oft made that the final product of the process is not known, so such endeavors are not very useful. The use of standards is one way to get around this. There is considerable concern as to the mechanism of failure for these devices. One may observe in Section 2.2c that the rate of degradation in the photocurrent (mA/cm^2) is the same in both the light and in the dark. It is not clear why the sample goes to zero in both sets of conditions in basically the same amount of time. One explanation is that light has nothing to do with the degradation phenomena—the system is just thermodynamically unstable, and the mechanism of degradation is kinetically accessible (independent of the interaction with photons, assuming dark conditions are actually dark and that there are no leaks, etc.). There exists a body of literature critiquing the value of "dark" experiments.

Question 4: Collaboration effectiveness

This project was rated **3.8** for its collaboration and coordination with HydroGEN and other research entities.

- Collaboration with EMN partners is extensive and well coordinated. The project is contributing to the HydroGEN Data Hub with information on chalcopyrite absorbers and n-type buffers.
- The collaboration between the PI and the HydroGEN consortium is effective. The different team members contribute complementary expertise to the project, which has resulted in obtaining satisfactory initial results.
- It is clear that there are multiple nodes engaged here, with each node essentially representing what could be a standalone project. The goals and impacts of each node are stated, but the researchers could benefit from a SMART approach.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- Future work is focused on critical barriers including improving protection layers, device integration, and printing new, higher-efficiency chalcopyrites.
- The proposed future work is a logical continuation of the Budget Period 1 work.
- The proposed future work is appropriate, as it focuses on key challenges identified on the first budget period. The discovery and integration of multiple chalcopyrite components in order to achieve >20% efficiency is well aligned with DOE goals, but a clear pathway to achieve this goal has not been identified. Stability is also very important to achieving the cost target, and the team intends to focus on surpassing the stability challenges faced in the first stage of the project. Device integration is necessary to demonstrate the potential of chalcopyrite materials in PEC devices.

Project strengths:

- This project has a very clever PI and is ambitious. The team appears to be meeting all of the milestones as they have been formulated. The researchers are attempting to select and employ/deploy significant discoveries/innovation in other fields (i.e., silver nanowires) to solve the problems in their own field. There appears to be some synergy between this project and others in the Program's portfolio.
- The project's strengths are as follows:
    - An inexpensive fabrication method for light absorbers
    - Simple assembly methods for multilayer devices through the use of hybrid polymeric materials
    - A good integration of team members and HydroGEN nodes, and the leverage of expertise from multiple team members
    - The early achievement of milestones, and a promising path to achieving the go/no-go points
- The EMN partnership and collaboration is excellent. There are solid accomplishments in materials processing, device fabrication, and stability.

Project weaknesses:

- This project is very complex and requires several substantial technical barriers to be retired simultaneously if it is to be successful. There are questions around the ability of the project to meet the cost targets. It is not clear that one could conclude that the technology does not work, even if the project proceeds through its entire planned life. Said another way: it is obvious when something works, but it is not always so obvious when it does not work.
- The project's weaknesses includes challenges for protection strategies under acidic conditions because of the roughness of semiconductor layers. Also, the initial demonstrated efficiency of the PV device is low and presents challenges for developing a 20% STH from chalcopyrite materials.

Recommendations for additions/deletions to project scope:

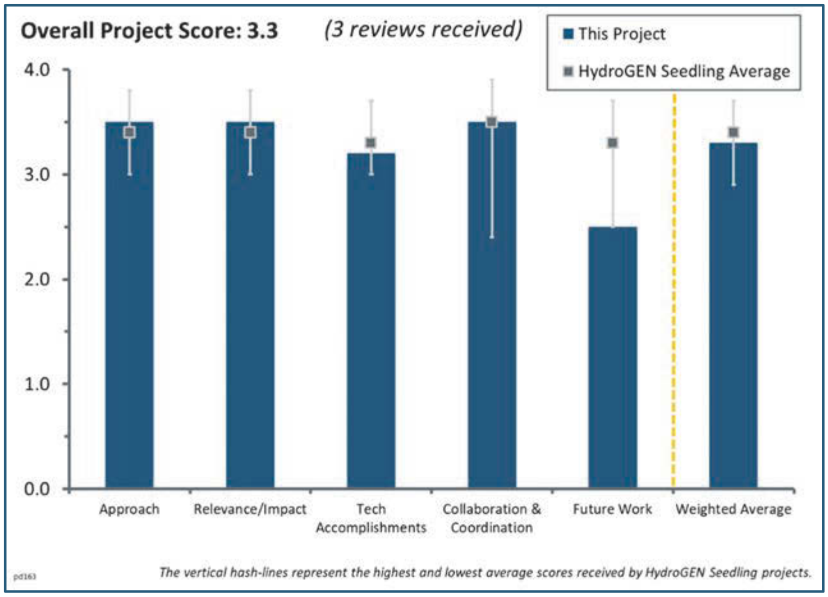
- Identifying a clear pathway to 20% STH is critical to achieving the project goals. Enhancing activities that lead to identifying such materials systems could enhance the potential for project success.

Project #PD-163: Monolithically Integrated Thin-Film/Silicon Tandem Photoelectrodes for High-Efficiency and Stable Photoelectrochemical Water Splitting

Zetian Mi; University of Michigan

Brief Summary of Project:

This project seeks to establish a low-cost and scalable platform for high-efficiency and stable photoelectrochemical (PEC) water-splitting devices and systems. The improved performance of the top photoelectrodes is required to realize high-efficiency, unassisted solar water splitting, and a functional wide bandgap tunnel junction that can be fabricated on a silicon platform is a critical component of a silicon-based tandem solar water-splitting device. The tandem photoelectrodes being developed in this project use silicon as the bottom light absorber and newly developed low-cost photoelectrodes made of Ta_3N_5, BCTSSe, or InGaN as the top light absorber. As silicon and gallium nitride are the two most produced semiconductors, the technology being developed will be scalable and lend itself to low-cost manufacturing.



Question 1: Approach to performing the work

This project was rated **3.5** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The project's approach is to place Ta_3N_5, BCTSSe, and InGaN top photoelectrodes on a GaN nanowire tunnel junction, and to demonstrate a double-junction photoelectrode on Si. The project utilizes resources from the Energy Materials Network (EMN) for modeling, materials diagnostics, in situ surface characterization, and catalyst deposition, as well as testing and stability analysis.
- Three barriers were identified: durability, integrated device PEC configuration, and scalable manufacturing of a monolithically integrated photoelectrode consisting of a bottom Si cell and a top light absorber with a 1.7–2 eV bandgap. The research approach is focused mainly on synthesizing multi-junction PEC materials based on Ta_3N_5, BCTSSe, and InGaN on Si and characterizing their interfacial properties. This approach is relevant to the barriers identified but lacks aspects of PEC device development and characterization. The Budget Period 1 activities related to the initial materials fabrications are designed to validate the proposed concept. While the photoelectrode development aspects of PEC technologies are important and are a key driver for the ultimate solar-to-hydrogen (STH) efficiency, equally important are device design aspects that have been overlooked in the current project.
- The approach is intellectually robust. In the hopes of keeping costs down, the project attempts to exploit the two most widely produced semiconductor materials in an innovative format(s). The project seems very academic. Budget Period 1 go/no-go decision points do have some metrics; however, the statement that "meeting these milestones will validate the concept...for the scalable production of solar hydrogen" is a leap too far to be supported by the milestones as presented. Scalability has to do with many factors not stated in the go/no-go milestones, one of which is production yield. There is no yield metric stated because there is no mature process for making these devices.

Question 2: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The objective of the project is well aligned with DOE goals. Developing high-performing, inexpensive PEC materials that achieve efficiencies >20% is a challenging task. The team proposes to achieve this goal by synthesizing multi-junction absorbers with cost-effective semiconductors. The team leverages multiple HydroGEN nodes to complement its expertise in surface analysis, computational materials modeling, probing interfacial phenomena, and deposition of electrocatalysts and protection layers.
- The project will attempt to address DOE efficiency goals by using high-efficiency, yet inexpensive, Si light absorbers. Top photoelectrodes will be passivated by a N-rich GaN surface (which is much more stable compared to the Ga-terminated alternative), which will attempt to address the DOE stability goals.
- Overcoming corrosion would be a relevant outcome. The best approach for doing this would be one that uses a system that is thermodynamically stable toward corrosion. Perhaps N-terminated GaN achieves this. However, if it is deposited as an ultra-thin protection layer, then the project is ultimately pursuing a kinetic strategy to inhibit corrosion. Specifically, it appears to seek a mass-diffusion barrier layer to prevent corrosion. This layer is an externally deposited layer, necessitating two things: (1) it must be absolutely defect-free, and (2) it must last for the entire lifetime of the device. These are objectives that, quite frankly, all projects pursuing such non-dynamically responsive kinetic barriers to corrosion are unlikely to meet. Much more sophisticated strategies have been developed for dynamically responsive, self-healing corrosion-preventative layers in the traditional metal alloy space. Perhaps learning could be gleaned from there. For example, the so-called alumina-forming alloys rely upon a reservoir of aluminum in their composition where that aluminum diffuses to the alloy surface and oxidizes, forming a dense, adherent, mass-transport (kinetic) barrier to further oxidation. If that kinetic barrier fails (spalls off), new aluminum atoms are there, ready to heal the site of failure before component failure can take off.

Question 3: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- The team has demonstrated significant progress during Budget Period 1. Computational models have been developed to demonstrate the role of N-rich surfaces in the improved stability of GaN. Top absorber films have been successfully grown, a method for Pt deposition has been developed, InGaN nanostructures with varying composition and bandgaps have been achieved, and InGaN photocathodes were fabricated on top of Si, demonstrating current densities as high as 12 mA/cm^2. These developments suggest a high probability of achieving the initial go/no-go criteria.
- The project has successfully synthesized and characterized various top photoelectrodes on Si wafers. It was unclear if/how the N-rich surface would be prepared to achieve stability.
- Theoretical modeling around N-terminated GaN stability toward corrosion is underway but still in its infancy. The presentation states that “theoretical models and interpretations will be validated by experiment,” yet it does not offer up which specific parameters will be stated by the model and measured by experiment, nor does it offer the quantitative level of agreement these two will achieve. Nice work was done on the atomically ordered InGaN deposition. When a non-aqueous method of catalyst deposition has to be developed to “reduce complications caused by catalyst growth in aqueous systems” but knowing the catalyst must ultimately operate in an aqueous environment, one becomes uneasy. It would seem that the synthesis of crystalline Ta_3N_5 thin films is an achievement; however, it is unclear whether these films have ever been synthesized before (by others). Also, the method of observing crystallinity (X-ray diffraction [XRD]) cannot quantify the degree of crystallinity. That is to say, if there are amorphous regions in the film, XRD will not do well to see it. Therefore, one may conclude that, yes, there is crystalline Ta_3N_5, but one may not conclude how much. It would not be good to risk visual/optical/scanning electron microscope images of grain pattern as a quantitative indication of the degree of crystallinity.

Question 4: Collaboration effectiveness

This project was rated **3.5** for its collaboration and coordination with HydroGEN and other research entities.

- Collaboration with the EMN looks extensive. This project has a specific plan to contribute to and benefit from the HydroGEN Data Hub.
- The collaboration in the team is strong, and the integration of HydroGEN resources in the project has benefited the outcomes of the project.
- The collaborations seem to be proceeding pretty much as expected; however, perhaps for reasons out of the control of the project team, data from the advanced light source has not yet been obtained. This makes it difficult to tie all the GaN-based phenomena together.

Question 5: Proposed future work

This project was rated **2.5** for its proposed future work.

- The objective of the proposed future efforts is the development of multi-junction photoelectrodes with >15% STH efficiencies and long-term stability. While these are worthy objectives, a clear pathway to achieve these goals is lacking. The initial performance achieved by the team suggests that a much lower efficiency should be anticipated.
- The proposed future work provides a general outline to overcoming barriers, although it is a little light on details.
- The articulation of proposed future work was inadequate, amounting to some high-level metrics and a budget number. The proposed future work slide does not make clear which scientific hypotheses have been tested and retained, versus which have been tested and retired. Scientific hypotheses may be retired for one of two reasons: either they are accepted by the broader community as the new null (baseline condition), or they are deemed “inadequate.” It is hard to track progress if hypotheses and the changes to hypotheses are not presented in the context of budget and time.

Project strengths:

- This project features strong collaboration between team members and effective leveraging of HydroGEN nodes, as well as significant progress on the synthesis of proposed materials and characterization of performance.
- The project excels at materials synthesis and characterization. The presenter showed a video of stable, unassisted water splitting, although it would have been beneficial to see data specifically relating to the performance and durability of that demonstration.
- This project has good materials science.

Project weaknesses:

- The initial performance is low and does not warrant development of a 15% STH device.
- More detail on the future work is necessary.

Recommendations for additions/deletions to project scope:

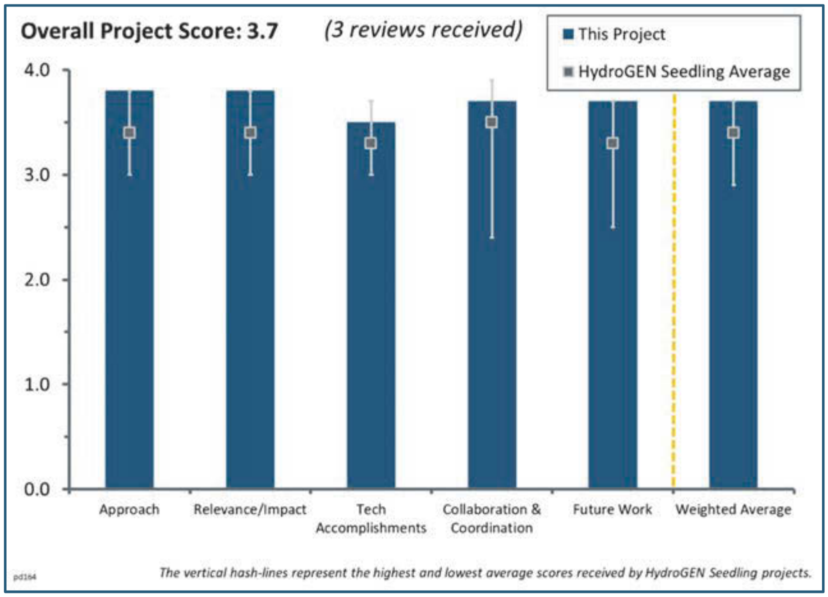
- Additional efforts should be devoted to developing high-performing photoabsorbers to develop a pathway toward the 15% STH goal.

Project #PD-164: Efficient Solar Water Splitting with 5,000-Hour Stability Using Earth-Abundant Catalysts and Durable Layered Two-Dimensional Perovskites

Aditya Mohite; Los Alamos National Laboratory

Brief Summary of Project:

This project builds on recent breakthroughs in high-efficiency perovskite solar cells and seminal work on using low-cost, earth-abundant materials for hydrogen evolution reaction (HER) and oxygen evolution reaction (OER) catalysts. Combining these two approaches enables the development of a disruptive low-cost photoelectrochemical (PEC) platform that would be a paradigm shift from the current state-of-the-art technology. The project goal is to develop a PEC device with solar-to-hydrogen (STH) efficiency of greater than 15% with 5,000 hours' stability.



Question 1: Approach to performing the work

This project was rated **3.8** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- This project is interesting, with some of the best "pure science" to which this reviewer was exposed. The "pure science" is being brought to bear upon a much applied problem: manufacturing processes do not produce perfect crystals. This project is one of the few that seem capable of portaging basic energy science over the saddle point into the applied realm. That is to say, this project/principal investigator (PI)/team seems capable of overcoming whatever the activation energy is that keeps so many of the discoveries in the basic sciences from finding their way into the applied. For example, the observed light-induced lattice defect correction (which may occur through photon–lepton–phonon "spooling") is a dynamic that is not some curiosity that lasts picoseconds or nanoseconds in a particle beam. No, this phenomenon is of a time constant (in minutes) that matters in the targeted application's timeframe. The approach was well done.
- The project has an intriguing approach and device design. It uses high-efficiency perovskite solar cells where the bandgaps are easily tuned. Anode and cathode will be connected in series in such a way that the two electrodes do not compete for light absorption. Since perovskites are notoriously unstable in water, the challenge will be adding a sufficient tunnel barrier that does not significantly increase recombination and resistance. This barrier/issue could have been emphasized a bit more. This is especially true since the goal is 5,000 hours of stability, which more stable materials have difficulty achieving. The project is well suited to be integrated into the HydroGEN network.
- The research approach relies on the incorporation of perovskite photovoltaics (PV) in PEC devices to obtain high STH efficiency with earth-abundant and inexpensive components at high efficiency. The team clearly defined a pathway to achieve this objective, and the project is divided into each of the components required for the development of the materials system. The go/no-go criteria for Year 1 was designed to evaluate the potential performance of the materials proposed for achieving high-efficiency solar water splitting.

Question 2: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- This project is very relevant and has potential for (long-term) high impact. Higher-yielding devices will occur if the defects in these devices can be photo-blotted out. Earth-abundant catalysts will be more cost-effective than those that are not—this is a classical approach to cost reduction. Cheap means adoption, which means impact. Since surface-based catalysis typically occurs at defects, lattice edges, or other surface protrusions (features), it seems that developing the capability to handle lattice defects can grow into an ability to focus phonons into coordinatively exposed transition metal centers, so that they may affect the desired reactions wherein the lattice is used as a reservoir of driving energy.
- The project is highly relevant to the DOE goals, and the incorporation of inexpensive, high-efficiency light absorbers such as perovskites can lead to significant cost reductions in hydrogen production from PEC devices. The project makes effective use of various nodes of the HydroGEN consortium to complement the PI's expertise in perovskite solar cells.
- The project uses high-efficiency, low-cost materials that have the potential to meet DOE cost and efficiency targets, assuming stability is achieved. The project is significantly leveraging Energy Materials Network resources.

Question 3: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and DOE goals.

- The team has made very significant progress toward the project's objective. A perovskite solar cell with solar-to-electricity efficiency >20% with a lifetime >1,500 hours was demonstrated. Effective protection strategies for the perovskite materials are being developed using graphene sheets, and MoS_2 layers were deposited via atomic layer deposition. Both MoS_2 and NbS HER and NiFe OER catalysts show sufficient performance for efficient solar water splitting. An integration strategy of the perovskite cells with electrocatalysts is being developed. The initial performance of the components developed provides high confidence for the achievement of the project's goals.
- The project is making good progress toward its milestones. Good fundamental improvements in perovskites were accomplished.
- Good progress has been made. The integration of the scientific innovation into the device (in ways that respect/preserve the physics) could occur more rapidly.

Question 4: Collaboration effectiveness

This project was rated **3.7** for its collaboration and coordination with HydroGEN and other research entities.

- The project is making good use of HydroGEN nodes and collaborating effectively in benchmarking, in situ characterization, modeling, and technoeconomic analysis. The team is also providing information on perovskites to the Data Hub.
- The collaboration between team members is strong and is reflected by the positive results from the first year of the project. The skillsets of all the investigators involved are complementary and are required for project success.
- Good collaboration is occurring, but it is sort of the "expected" kind of collaboration. The collaboration is typical.

Question 5: Proposed future work

This project was rated **3.7** for its proposed future work.

- The proposed future work is reasonable and is likely to lead to the achievement of project goals. The materials integration strategies being sought are appropriate for the development of the intended high-efficiency device. Characterization activities can provide insights into charge transport and degradation mechanisms that may limit the performance of the stability of the devices. Ultimately, characterizing STH efficiencies of the perovskite devices will be important to assessing the potential of the materials explored.

- The proposed future work is a logical extension of the prior year's work. The use of perovskite-/Pt- and Ir-based catalyst systems should probably be only a short burst of effort to create a benchmark with sufficient character and measurement count so as to enable future innovations to be held in statistically significant comparison. Understanding charge transport and degradation mechanisms will be very important; they are likely complex phenomena with multiple contributors and multiple space and timescales of action. Additional clarification on the strategies to be employed here would have been useful.
- The proposed future work addresses the remaining barriers.

Project strengths:

- This project has strong team integration and leverages HydroGEN nodes well. There is promising performance of the light absorber material with >20% PV efficiency, as well as demonstrated performance of HER and OER components. The light absorber also has long-term stability.
- This is a great project with a very talented PI and a strong project team. There are some fascinating innovations developing here, and the collaborations across the national laboratories seem to be building out upon these.
- This project, if successful, would provide a new paradigm for solving PEC challenges. This goes beyond incremental change.

Project weaknesses:

- Device design aspects are missing from the proposal. Mainly, the advantage of integrating perovskites with electrocatalysts, as opposed to developing PV electrolysis cells, is not clear.
- The involvement of students could have been better emphasized.

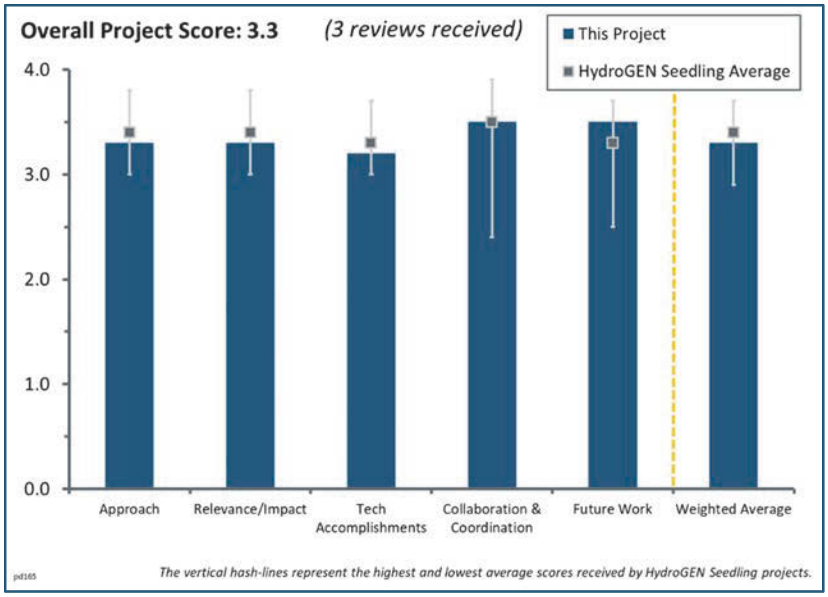
Recommendations for additions/deletions to project scope:

- Given the high performance of the light absorber, it may be important to increase the emphasis of the device design and development activities, to guarantee that the potential gains in the PV are not lost as a result of device-related factors (e.g., electrolyte resistance or poor light management).

Project #PD-165: Accelerated Discovery of Solar Thermochemical Hydrogen Production Materials via High-Throughput Computational and Experimental Methods

Ryan O'Hayre; Colorado School of Mines

Brief Summary of Project:



The current state-of-the-art solar thermochemical hydrogen (STCH) material efficiency is approximately 2%, but development of an optimal STCH material could increase the efficiency beyond 60%. This project aims to integrate combinatorial synthesis methods with combinatorial theoretical calculations to rapidly discover new potential materials for use in two-step metal oxide cycles for STCH. The effort builds on prior collaboration between the project partners, which resulted in the discovery of two novel perovskite-based STCH candidates, and leverages the Energy Materials Network (EMN) model of merging high-throughput computational and experimental techniques to accelerate new materials discovery.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The outlined approach is well-thought-out and innovative and may lead to success. The project has leveraged multiple appropriate HydroGEN nodes in pursuit of the project goals and is well integrated into the HydroGEN consortium. The project has strongly demonstrated the collaboration and the use of these HydroGEN nodes in achieving goals. The work in Budget Period 1 has achieved the goal of demonstrating the computational approach, and as such, the ability to identify a new material, "Material X," which has achieved the first go/no-go criteria. The experimental work has also demonstrated the use of optical analysis for the presence of reduction/oxidation. It is here where further approach refinement is necessary; in rapid screening of materials, it is necessary to know the extent of reduction/oxidation, in addition to a binary analysis of whether it occurred. This could be achieved through additional non-optical spectroscopic techniques such as X-ray photoelectron spectroscopy (XPS). The project should also identify a workaround to the high-temperature diffusion and thus substrate/thin film mixing. This newly identified barrier needs to be overcome for project success.
- The idea of using combinatorial thin film deposition of up to four targets seems to be a very interesting method for identifying more reactive materials for STCH processes. The integration with excellent theoretical capabilities forms a strong partnership to deliver important results. However, the color change seems to be an easy way to find good candidates, but the reality is more complicated. The link to other groups working in the same field in HydroGEN could be improved.
- Project barriers are understood, and some new approaches are proposed. The combinatorial approach is promising if the results can be trusted. It was not clear from the slides what the innovation is in the density functional theory (DFT) screening part.

Question 2: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- This project is well aligned with the DOE project goals of identifying new materials. The rapid screening, both experimental and computational, has the potential to identify new materials if the barrier can be overcome. The team has excellent collaboration and leveraging of DOE resources. This is aided by the team's close proximity to National Renewable Energy Laboratory, which has enabled personnel exchange and training. Additionally, long-standing collaboration with Dr. McDaniel at Sandia National Laboratories (SNL) and modifications to allow for remote accessing of equipment has enabled the team to make excellent use of the stagnation flow apparatus. However, the team should start considering technoeconomic analysis to achieve the DOE cost targets.
- The combination of combinatorial chemistry and high-class simulation forms a strong synergy in this project. The impact on the goals has the potential to be very high. A better connection to the other projects in the field in HydroGEN would make this even better.
- Materials discovery is the key challenge for pure thermochemical cycles. Perovskites are the most prospective material to do better than ceria, but the number of permutations is bewildering. Any effective and, most importantly, reliable screening method could lead to a big step forward.

Question 3: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and DOE goals.

- Significant progress has been made toward the DOE goals. The project has completed preliminary assessment of materials and has identified an interesting new material. The team has also demonstrated the project's computational approach and some of the experimental approaches. The team has demonstrated excellent collaboration with the consortium. However, the team does need to demonstrate combinatorial deposition and quantitative measurements of reactivity, as this is critical to project success. This likely depends on new developments to prevent interaction with the substrate, as well as more concrete analysis techniques.
- The project seems to be on a very good path. There is confidence that the team will meet the go/no-go criteria. The presented work makes this statement probable.
- Slide 14 suggests that a promising material has been identified, though the performance drops significantly at realistic water-to-hydrogen ratios. Slide 13 indicates that the reduction is done with hydrogen well below the target reduction temperature (1000°C versus 1350°C). It is unclear whether this is representative of high-temperature reduction (and at what temperature). It is also unclear whether this optical test is repeatable with sequential reduction and oxidation cycles. It was also observed that the substrate (not specified) may also be interacting with the material at these temperatures (which is presumably why hydrogen is used as a reductant to reduced peak temperature). Slide 12 suggests that the DFT work is reasonably well understood, but it is unclear whether the project is using innovation or just leveraging existing expertise.

Question 4: Collaboration effectiveness

This project was rated **3.5** for its collaboration and coordination with HydroGEN and other research entities.

- The collaboration in the project is excellent. A strong practical and theoretical team has formed, one that seems to work efficiently together. The connection within HydroGEN could be improved by closer cooperation with the other projects working in the same field.
- The group has made outstanding use of the HydroGEN nodes and shows a highly integrated approach to the project. The group is utilizing the Data Hub. The project team needs to be more explicit about their Task 2b activities in regard to protocol development, as these were not directly obvious.
- The project seems to be effectively leveraging expertise at other institutions.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The project has a well-thought-out plan and approach for future work, given the milestones/deliverables as stated. To meet DOE's goals, it is recommended that the team amend this plan to include further research into how to accomplish, in a quantitative way, the experimental combinatorial analysis, particularly reduction/oxidation activity quantification and film stability. This will then require amendment of the plan, but based on performance so far, it seems that the team will be able to successfully do this and plan for it.
- The proposed future work has clear targets that would have a strong impact on development in the field of active perovskites for STCH processes. In particular, the transfer into a Hydrogen Analysis (H2A) effort promises a close connection to application toward the end of the project.
- Year 2 appears reasonably well scoped, but Year 3 is not very explicitly explained. This is not a major issue, as "Full characterization and advanced study of excellent candidate, including H2A" is a reasonably significant undertaking.

Project strengths:

- The project strongly leverages DOE resources. The team has not only used DOE facilities but learned new techniques and brought them into their laboratories, and has contributed likewise by helping to exercise remote access capabilities at the SNL stagnation flow reactor facility. The team has identified a new material based on project screening and has ideas of the desired material's properties.
- The project seems to be effectively leveraging the expertise in the EMN network and has some good ideas and outcomes so far.
- The combination of combinatorial chemistry with advanced simulation tools is a project strength.

Project weaknesses:

- As with all the HydroGEN projects, there has been limited interaction between the projects, as opposed to with the EMN network resources. It is not clear where some of the innovation lies and how robust/useful the optical characterization is.
- The greatest project weakness is the experimental rapid screening. This needs to become quantitative rather than qualitative, and diffusional/thin film stability issues need to be resolved.
- Color changes seems to be a rather simple method to determine the right materials. The project could use a better connection within HydroGEN.

Recommendations for additions/deletions to project scope:

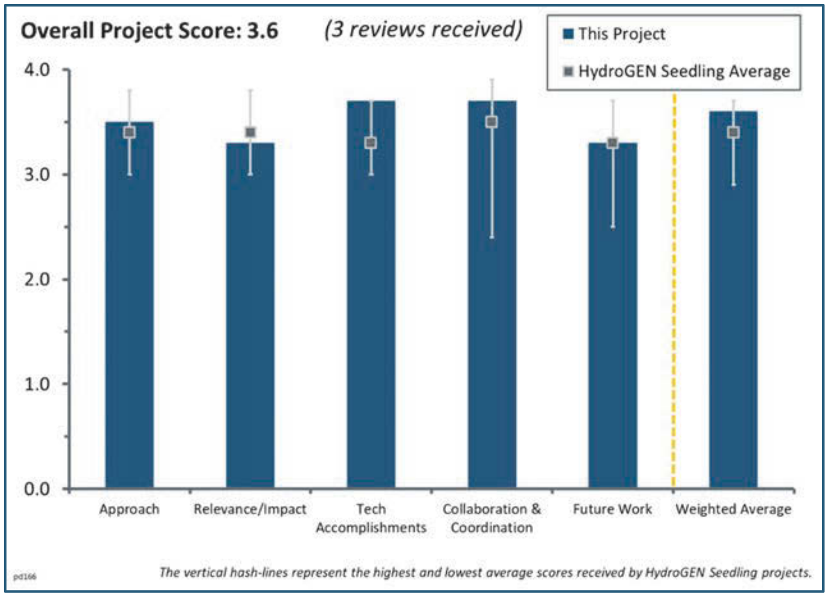
- The project scope is excellent and should be followed as is.
- The project scope should be modified to make the experimental screening of materials quantitative rather than qualitative. Additionally, the kinetic aspects of materials should be further assessed. Lastly, in-depth thermodynamic characterization of materials is needed (i.e., the determination of partial molar enthalpies and entropies). This characterization will enable thermodynamic modeling of the system and, thus, system optimization and materials efficiency comparisons.
- It is not clear how the combinatorial thin film screening really fits in, as the samples shown have rather uniform color. It would have been more interesting to see whether the color shows gradations with changing stoichiometry.

Project #PD-166: Computationally Accelerated Discovery and Experimental Demonstration of High-Performance Materials for Advanced Solar Thermochemical Hydrogen Production

Charles Musgrave; University of Colorado Boulder

Brief Summary of Project:

The project objective is to utilize machine-learned models coupled with ab initio thermodynamic and kinetic screening calculations to accelerate the research, development, and demonstration of new solar thermochemical hydrogen (STCH) materials. The approach will rapidly screen a vast number of new candidate metal oxides materials for stability, thermodynamic viability, and kinetics. The project will utilize experimental techniques to evaluate thermodynamic and kinetic properties of new materials to provide feedback to the computational thermodynamic and kinetic screening effort.



Question 1: Approach to performing the work

This project was rated **3.5** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The project is using a very appropriate way to tackle the problem: searching materials beginning with machine-learning thermodynamic basics and conducting thermodynamic and kinetic screening validated by experiments.
- Given the enormous challenges in identifying practical STCH materials, the use of machine-learning may be appropriate and timely for screening the vast combinations of multi-metal oxides.
- The barrier identified is just the large number of compounds that need to be screened. Thus far, no materials exhibit the required activity at a reasonable temperature. Aside from this, the project seems well scoped. It is interesting to see some attempt made to compute kinetics, which has always been difficult without experiment. The target reduction temperature is still a bit on the high side.

Question 2: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- This approach is very relevant and its impact probably very high. However, there are alternatives in HydroGEN that should be linked more closely to this work. The combined work of all projects on materials in HydroGEN would be outstanding.
- Finding a suitable redox material is the key challenge for this technology. Therefore, the project is appropriately targeted (providing a good system efficiency can be obtained at such a high temperature).
- The project goals are relevant and in alignment with the Energy Materials Network (EMN) and Advanced Water Splitting Materials consortium objectives. However, given the novelty of this approach, the potential impact is difficult to assess at this point.

Question 3: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and DOE goals.

- The project already presents outstanding results. These results promise that in the next phase of the project, important contributions to HydroGEN will be provided.
- The project seems to have made very good progress in machine learning to improve prediction of stability. There are still many candidates. Slide 13 of the presentation indicates a number of candidate materials with good performance, although the steam-to-hydrogen ratio (and variation in performance with same) is not mentioned.
- The project team has accomplished a good deal so far. However, since this project is likely to set standards for other similar materials screening efforts, it would be helpful to discuss and share the reasons for choosing the particular machine-learning algorithm over others.

Question 4: Collaboration effectiveness

This project was rated **3.7** for its collaboration and coordination with HydroGEN and other research entities.

- The project has an outstanding collaboration concept. It includes partners from outside the HydroGEN team and even international partners. This enables the project to harvest a wide and world-class contribution to the development of efficient materials for the STCH processes.
- The current collaboration effort looks appropriate, but it is suggested that the project team keep the option for other collaborators as needed, given the novelty of this approach. One such option is to seek partners with combinatorial materials synthesis or characterization capabilities to accelerate experimental efforts.
- The project is collaborating effectively both within and outside the EMN network.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work is excellent; it contains all aspects to achieve the project goals.
- The project team seems clear on objectives and activities for subsequent years.
- The proposed work looks reasonable, especially the focus on time-based hydrogen production rates. However, it is hard to understand the basis for the stated milestones. For example, it would be helpful also to provide current thinking on commercially acceptable hydrogen production rates from such systems. In addition, the team should start incorporating cost factors into their screening tools.

Project strengths:

- This is a sound combination of basic theoretical work and experiments. The team shows excellent collaboration, even with international partners.
- The project team seems to have a good handle on and understanding of computational thermodynamics and kinetic screening of these STCH materials.
- Machine learning seems to have improved model predictions of stability. The team has good collaboration with other experts in the field, both in and outside the EMN network.

Project weaknesses:

- This is a relatively high target reduction temperature, and it is unclear how the materials would perform at moderate water-to-hydrogen ratios. This will be critical for overall cycle performance.
- The collaboration within HydroGEN could be improved. Similar to other projects in the Hydrogen and Fuel Cells Program, the lack of collaboration with HydroGEN is due to limited time.
- There is an apparent weak mismatch of feedback loops between computational and experimental efforts.

Recommendations for additions/deletions to project scope:

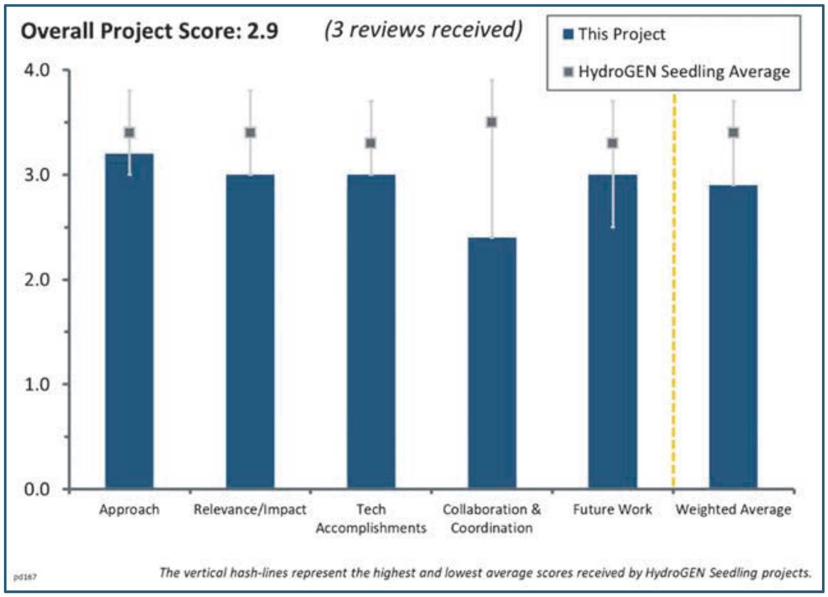
- In addition to thermodynamic and kinetic parameters, the team should consider material cost as a parameter for screening the STCH materials. Having some idea of system cost based on promising materials is also desirable, although it may not be in scope for this project phase. If possible, the project team should also consider acquiring combinatorial synthesis and/or testing equipment to accelerate the experimental work or collaborate with a laboratory that has such equipment.
- The work plan seems to be appropriate. Additions or deletions do not seem to be necessary. An exchange between the other projects on the materials topic seems to be valuable.
- As with all the HydroGEN projects, there is not enough interaction with the others. The four materials discovery projects in oxides should get together in a facilitated environment to get the most out of the work at the various institutes.

Project #PD-167: Transformative Materials for High-Efficiency Thermochemical Production of Solar Fuels

Chris Wolverton; Northwestern University

Brief Summary of Project:

The project objective is to utilize a computational–experimental approach, combined with materials design strategies to quickly discover and demonstrate novel thermochemical materials with properties superior to the state of the art. The project will investigate what is an enormous compositional space of materials utilizing high-throughput computational and experimental methods to identify promising compounds that show (1) ground state stability/ synthesizeability, (2) thermodynamics favorable for <1400°C reduction, and (3) thermodynamics favorable for facile water splitting.



Question 1: Approach to performing the work

This project was rated **3.2** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The work itself is excellent. The combination of experiments and theoretical work to create a database of possible active and stable perovskites points exactly in the right direction of HydroGEN. The work is already very advanced; it even shows some of the limits, as the number of elements determines the possible materials. The connection within HydroGEN does not seem to be as good as it could be. There are a number of other groups working in the same direction that are not linked to this work. Together, the work would be even stronger.
- The approach as demonstrated in the slides and poster represents marginal improvements to materials development, with the only seeming major advancement coming from examination of double perovskites. The methodological approach seems to be no different from the currently taken approach to materials identification. Computational methods use traditional density functional theory methods to screen materials, generate all possible structures, calculate them, identify stable materials, and then calculate oxygen vacancy formation energies. This process lacks a method for accelerating screening other than a brute force method, which is likely intractable as the phase space expands. The brute force method has identified novel double perovskites that have not been suggested before; however, there is no indication, experimentally or computationally, that these materials will facilitate water splitting. Selection of materials for analysis is based on materials that fall within a wide range of oxygen vacancy formation energies and, seemingly to an equal extent, chemical intuition. It seems that just computational identification of any material that can split water is the desired computational end goal, rather than materials that do so efficiently or cost-effectively. Experimental work to date has relied on traditional thermogravimetric analysis (TGA). The principal investigator (PI) indicates that more rapid techniques will be used in the future, but there is no demonstration of this or validation of the approach. There is little to no interaction or integration into the HydroGEN consortium. The use of nodes seems to be an afterthought at best. Rather than selecting complementary capabilities, the PI seems to have selected nodes with capabilities similar to the project team's own expertise.

- As with the four other projects in this space, this work relies heavily on high-throughput DFT modeling. This project has some slightly different approaches, but it is hard to judge whether this project is using a better approach than the others. A forum of the teams should be convened to discuss pros and cons of the various approaches. The recognition that phase change may improve performance is notable, as the challenge with non-stoichiometric reduction is low production rates. Naturally, long-term cyclability is the question.

Question 2: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The potential for this project is very high. The project has a very interesting strategy for down-selecting possible materials as candidates for efficient STCH processes. The probability of finding the right candidate materials is rather high. However, the link to work that is more focused on the application is missing. This would add criteria that could be used in the selection matrix to narrow the candidate materials further down.
- The project is relevant and is working toward developing materials that split water. The development of new materials, such as the double perovskites investigated here, would represent a major advance in the STCH community. However, the project seems to focus on expensive rare earths for use in the materials. This will likely pose a challenge in terms of meeting the price goals and scale-up goals. To date, the project does not leverage HydroGEN consortium resources.
- Finding a suitable redox material is the critical challenge in this area. The team nominates 1400°C as the reduction temperature, which is still quite high for achieving good cycle efficiency. However, the overall cycle configuration, including recuperation, kinetics, and reactor design, will be vital also.

Question 3: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The work is very advanced, and the results are already very impressive. The methodology is well described. The theoretical results are validated by experiments. The work is a very valuable addition to the HydroGEN program.
- Overall, there is good correlation between computational prediction of reduction and experimental measurements. Correlation between perovskite distortion and vacancy formation energy is useful.
- The project has made progress. The team has shown that some materials predicted to be stable are stable. The project has also shown, via a feedback loop, that if the calculations are done correctly (i.e., simulate the correct phases), the oxygen vacancy formation energy can be predicted with reasonable accuracy. Without careful consideration of the active phases, calculated formation energies do not match. This has informed the project leaders of the importance of careful phase determination. The go/no-go metrics are very weak. The project easily met the stability criteria. The project met the correlation between the experiment and theory through an iterative computational approach.

Question 4: Collaboration effectiveness

This project was rated **2.3** for its collaboration and coordination with HydroGEN and other research entities.

- There is good collaboration with Energy Materials Network node resources, as per the others. In the next stage, collaboration between the HydroGEN projects should be a key focus to really accelerate the work.
- All of the work to date has been completed at Northwestern University. Use of nodes or HydroGEN capabilities is an afterthought and considered at all only because it is a project requirement. The project proposes use of three nodes, one of which has significant overlap in capabilities with Northwestern University.
- The collaboration within HydroGEN is satisfactory. There is a cooperation with three complementary groups, but the link to other projects working in the field of innovative methods for materials selection seems to be rather weak. Both the project and HydroGEN would benefit if the different projects were able to work more closely.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed work for Years 2 and 3 is excellent. This project has the potential to produce very valuable results. However, the potential could be improved if the link to the other groups working in the field were strengthened.
- The future work is planned within the project scope. Computational work will continue and focus on calculating oxygen vacancy energies in a logical and thought-out manner. The experimental future work plan is either weak or poorly communicated within the team and, therefore, poorly communicated externally. This makes it difficult to fully evaluate. If future experimental work is merely TGA, then this work is insufficient for assessing materials. If it includes other methods of materials assessment, that is completely missing from the documentation or Year 1 validation of the plan. The project needs more concrete goals/materials identification criteria to aid in materials selection such that DOE efficiency and cost goals are achievable. Additionally, future work should include closer collaboration within the existing team and between the team and HydroGEN partners.
- This project is very much focused on the discovery side, with limited performance characterization in terms of hydrogen evolution.

Project strengths:

- This project's strength is the consideration of double perovskites; these materials have not yet been reported on within the STCH community. The project has identified many new stable double perovskites.
- This project has an innovative methodology that is able to provide a down-selection of materials based on theoretical high-throughput DFT calculations.
- This project has done nice work to date and shows good progress.

Project weaknesses:

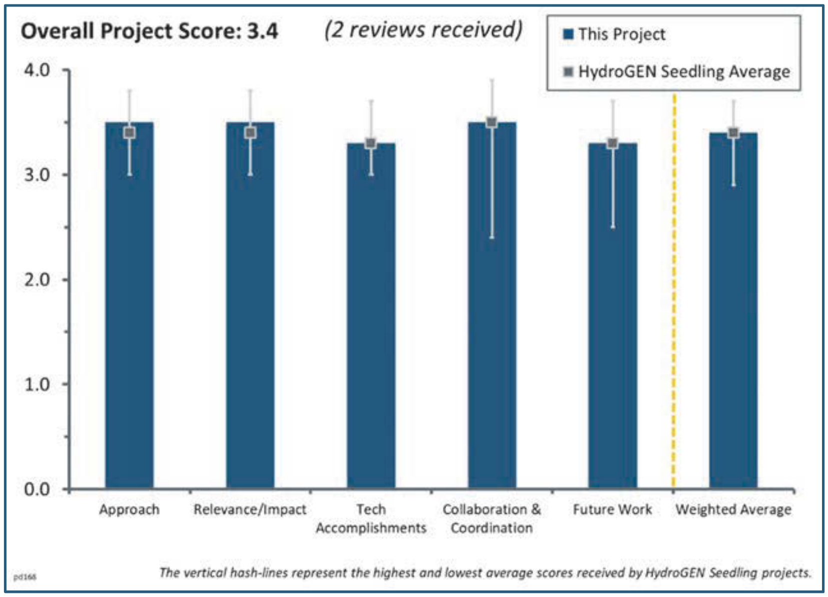
- This project has multiple areas for improvement. The largest is the use of the national laboratory nodes. This seems to be completely lacking, and it seems that the project would rather not have to interface with teams outside of Northwestern University. The communication between the computational and experimental work also needs to be improved, both in terms of collaborative goals and understanding of each other's methods and tasks. Also, the team should refine the desirable materials characteristics that will not only enable materials identification but also provide a chance of production at scale and cost targets. While massive time does not have to be devoted to the cost of hydrogen production in a materials identification project, it should at a minimum be a consideration of the team. The team should also consider methods for accelerating materials screening and analysis beyond brute force methods for both computation and experiment.
- The project seems to be not very well connected in the HydroGEN program. Perhaps this is a problem of the tight schedule of the program.
- It is unclear whether the project has considered relative abundance of the elements in the screening group.

Recommendations for additions/deletions to project scope:

- The scope of work is excellent. The only thing to add would be a better exchange with other projects.
- As with the other computational projects, a forum of the different projects should be held where the researchers can debate which techniques have more general relevance to try, accelerating progress across all groups. This project could also benefit from adding some performance evaluation (e.g., with A. McDaniel at Sandia), as with other projects.
- The project scope should consider the kinetics of the materials as well as some tasks on hydrogen production costs. Additionally, explicit tasks incorporating national laboratory nodes should be included.

Project #PD-168: Mixed Ionic Electronic Conducting Quaternary Perovskites: Materials by Design for Solar Thermochemical Hydrogen

Ellen Stechel; Arizona State University



Brief Summary of Project:

The project objectives are (1) to contribute to improved solar thermochemical hydrogen (STCH) materials discovery by providing strategies to boost solar-to-hydrogen thermal efficiency and (2) to provide experimentalists with crucial input to synthesize, validate, and perform further testing on promising candidates. The project will apply first principles computational materials design capability to calculate and validate chemical potentials for complex off-stoichiometric redox-active mixed ionic electronic conducting perovskite metal oxides. The end goal is to determine design principles for optimal and discoverable materials that have the potential to perform better than ceria, meet the target efficiency (solar-to-hydrogen thermal efficiency >30%), and approach the ultimate production cost goal of < \$2/kg H_2.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The project seems well scoped, with an interesting new way of looking at the problem. The key impact areas remain a significant challenge, in terms of how to get to a sufficiently high delta (>0.15 per cation, cf. ceria at 0.03) at a realistic temperature (1450°C is still very challenging).
- The project is a mainly theoretical attempt to find suitable materials for STCH processes. The theoretical work is linked to practical evaluation. However, the goal seems too realistic to reduce the necessity of extensive material synthesis.

Question 2: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The project's models will be a very valuable contribution to HydroGEN. However, there are competing attempts that could jointly form a real outstanding network.
- Materials discovery is the critical challenge for this team, as with the other four projects looking at oxide cycles. Redox cycles are not realizable without a significant improvement in active material performance.

Question 3: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and DOE goals.

- There appears to be a significant improvement in understanding, though the reviewer is not an expert in the intricacies of density functional theory. The project's milestones are on track.

- The achieved results are very important. However, there seems to be a slight delay in the project. This is not severe, and it is probable that the project will achieve its milestones.

Question 4: Collaboration effectiveness

This project was rated **3.5** for its collaboration and coordination with HydroGEN and other research entities.

- There is excellent collaboration between the partners, as well as very efficient and honest coordination that anticipates the developments within the project.
- Collaboration seems to be well coordinated and taps into key expertise (slide 9). This is not as clearly articulated as in some other projects, which explicitly draw out Energy Materials Network (EMN) node interactions, but the collaboration seems to be appropriate and effective.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The future work is very well defined and seems to be absolutely appropriate to achieve the project's goals. The work is important, and the possible impact is very high.
- Slide 19 lists many planned activities, but it is not clear from the presentation how they are to be structured over Years 2 and 3. This is likely to be explained elsewhere (e.g., the DOE project plan), but it is not in the reviewer materials.

Project strengths:

- The project team appears to have gained some clever insights into how to better use computational methods to identify the goldilocks material. There is a good understanding of fundamentals.
- The project team has excellent theoretical capabilities and project management. There is a strong link within the project consortium.

Project weaknesses:

- This may not be an actual project weakness, but the reviewer material was not that focused on addressing reviewer questions in terms of EMN collaboration and detailed project planning. Technically, the project seems to be excellent work, although (as with others) it could benefit from peer discussion between the HydroGEN projects.
- This project lacks a link to other projects on the same topics within the HydroGEN Consortium.

Recommendations for additions/deletions to project scope:

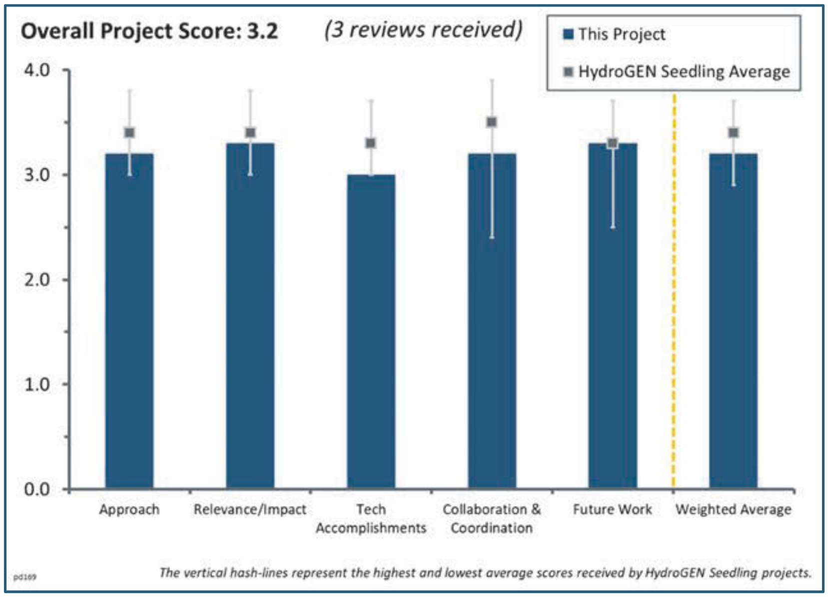
- The project is excellently defined, and no additions or deletions seem to be appropriate. As with all projects in the HydroGEN Consortium, a closer collaboration between the projects would strengthen the joint results.
- As per slide 9, the proposed future work does not include experiments at Sandia National Laboratories (slide 19), which indicates the stagnation flow reactor will be used. This should be clarified.

Project #PD-169: High-Temperature Reactor Catalyst Material Development for Low-Cost and Efficient Solar-Driven Sulfur-Based Processes

Claudio Corgnale; Greenway Energy

Brief Summary of Project:

The project objective is to develop an efficient and low-cost solar thermochemical process. In particular, this project is focused on the solar-driven hybrid sulfur (HyS) cycle and the development of catalytic materials to decompose sulfuric acid, a critical step in this two-step water-splitting cycle. The project will (1) develop a new catalyst material using the team's demonstrated surface free energy and electro-less deposition technique; (2) design a novel, integrated, direct solar reactor–receiver, based on a demonstrated cavity solar reactor, and (3) perform system and cost analysis on an effective new solar–thermochemical plant process.



Question 1: Approach to performing the work

This project was rated **3.2** for identifying barriers and addressing them through project innovation, project design, feasibility, and integration with the HydroGEN Consortium network.

- The project is unique in the field of solar thermochemical hydrogen (STCH), as the team is not only developing innovative ways to identify promising materials for water splitting but also looking at how such materials will be used in real applications. The sulfur-based processes are different from the metal–oxide cycles, as the materials necessary are catalysts and not reaction partners in the redox cycles. The work in this project is mainly on the stability and efficiency of the catalyst materials. However, this seems to be rather straightforward. Sulfur chemistry is a major topic in the chemical industry. A joint development with industry seems to be appropriate to accelerating the catalyst development. The strength of the project clearly lies in the integration attempt to describe how the materials could be efficiently used in even very large-scale applications on the several-100-MW scale. The link from materials development to how these materials are used is unique in the HydroGEN Seedling sub-category. The proposed receiver reactors seem to be very promising, and the design of different-size solar towers for hydrogen production is the key to successfully getting STCH into application. For the short time the project has been running, excellent results were achieved concerning the system, but the material development seems to be not as advanced.
- The project has identified the key areas for resolution of the solar thermal component of the HyS process. No mention is made of the electrolyzer, apart from slide 16, but this is not a major omission. In fact, the scope is already much broader than other HydroGEN projects and is much more applied.
- This project has several components, all integrating into a single overall reactor design to achieve U.S. Department of Energy (DOE) targets. Each individual piece of the project seems to be moving forward and seems to be on pace to accomplish the stated objectives. The team's work so far for budget period 1 is good and mostly demonstrates feasibility. In particular, the novel fin-based reactor concept stood out. This could be widely expanded into other solar technologies. Similarly, the novel HyS flow sheet represents a significant step forward in terms of economic and energetic efficiency. However, the main innovation seems to be coupled with inventions from a separate DOE project rather than results/innovations from this project. The weakest piece seems to be in terms of catalyst development. The catalytic material is still

dependent on expensive Pt group metals, and there is little fundamental development on how/why the catalysts are deactivating. It seems that the innovation is in the deposition method and just hoping for limited deactivation of the materials. It would be helpful to see the behavior of "baseline" materials. Lastly, more direct integration of the team and cross-level interaction would be desirable.

Question 2: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program goals and the HydroGEN Consortium mission.

- The systems work is excellent and unique within the HydroGEN consortium projects. The other projects, and the development in general, will strongly benefit from this work. In this respect, this is dominant to the materials development—which is not much connected to other work under this framework because it deals with different substance classes.
- This project has some high-potential-impact components and is appropriately placed in the HydroGEN consortium. It looks like the systems analysis, manufacturing, and integration will potentially enable the achievement of DOE goals. The project lacks novel catalyst materials development and instead focuses on catalyst fabrication techniques. Not only does this project have the potential to leverage DOE resources at the national laboratory, but it could also be very interesting to other HydroGEN consortium partners.
- The HyS process is highly prospective for STCH production, as it is likely to achieve the highest solar-to-chemical conversion of any cycle and requires a much more moderate temperature than metal–oxide cycles.

Question 3: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and DOE goals.

- The project has already achieved substantial results. It seems to be on a good track to stay within the foreseen project plan. Levels 2 and 3 are unique within the project and are, therefore, outstanding in this respect. Level 1 is sound catalyst work, but it lacks uniqueness.
- It is not clear whether all the work in the three areas was able to be done in the few months available and how much was possible by tapping into work that was partially complete. All the same, the achievements for the Level 2 and 3 areas are impressive and represent good progress. The catalyst work described in Level 1 is, in contrast, rather unimpressive and in sharp contrast to some of the other HydroGEN projects, which are true materials discovery efforts. The catalyst work in this project seems rather linear and does not really include any innovation in terms of materials screening or experimental design.
- Large strides have been made in some areas of the work. Level 2 and 3 technologies seem to be moving forward very well and are on pace to achieve the targets. Level 1 catalysis development is behind. Any results of the fabricated $Pt/Ir/TiO_2$, in terms of reaction, should have been shown to allow assessment of whether these materials are capable of catalyzing H_2SO_4 decomposition. Similarly, it is unclear whether the Pt deposits on the Ir/Ru as a sheet (as desired) or in islands. Lastly, the go/no-go criteria and the relevant progress should be clearer.

Question 4: Collaboration effectiveness

This project was rated **3.2** for its collaboration and coordination with HydroGEN and other research entities.

- The coordination and collaboration in the project seem to be excellent. The organization of online and in-person meetings are appropriate for the collaboration. The input into DataHub is of high relevance, especially as data are provided for the technology development, which could be a starting point for other projects to scale up their technologies.
- It is not clear whether the collaborations in this project have been facilitated by the establishment of the Energy Materials Network (EMN) or represent existing ties between the researchers. Despite this, the collaborations are appropriate (in terms of tapping into key resources) and appear very effective.
- Collaboration within each level shows very good interactions between the nodes and the recipients. These interactions seem separate rather than fully integrative. More interaction between the levels should be

sought, both with the recipients and between the recipients and the nodes. This will help the project act more like a single work rather than three separate projects under one umbrella. The team also uses the Data Hub.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project team presented a good plan for moving forward and achieving project goals. The plan follows the logical next steps toward DOE targets. More aggressive catalysts/materials goals should be set, however, and more attention should be paid to this progress.
- The proposed future work is straightforward. It will definitely improve the results and is absolutely necessary for a development closer to application. In this respect, topics such as the long-term stability of catalysts, testing of receiver reactors, optimization of flow sheets, and assessment of alternative solutions are typical future work packages. However, the proposed work lacks the potential for breakthroughs.
- The biggest issue with the proposed future work—which would provide some valuable information—is clearly the very broad scope and the fact that much of this work appears to be beyond the available budget (slide 22). The catalyst work that fits most closely with the other projects in HydroGEN probably should be a bit better explained in terms of the rationale and methodology. It is not clear how the catalysts are selected and optimized and whether this is from prior work.

Project strengths:

- The project team has achieved very interesting results in the new catalytic reactor design and system integration; this has led to the patenting of new technologies. These improvements go a long way to achieving the overall goals. The team also has strong intra-level collaboration and is using nodes to achieve the project goals.
- The strengths of this project are clearly in the development of receiver reactors and the systems. These are unique throughout the whole consortium, and the result will be very important to other groups, helping them to develop their technologies on the next level. Also, the project management and communication of the project seem to be excellent.
- The HyS process is extremely promising for solar hydrogen production. This project seeks to improve knowledge in three key areas. There is excellent collaboration with national laboratories that taps into an enormous competency for this process, which would be a shame to let languish and fade away.

Project weaknesses:

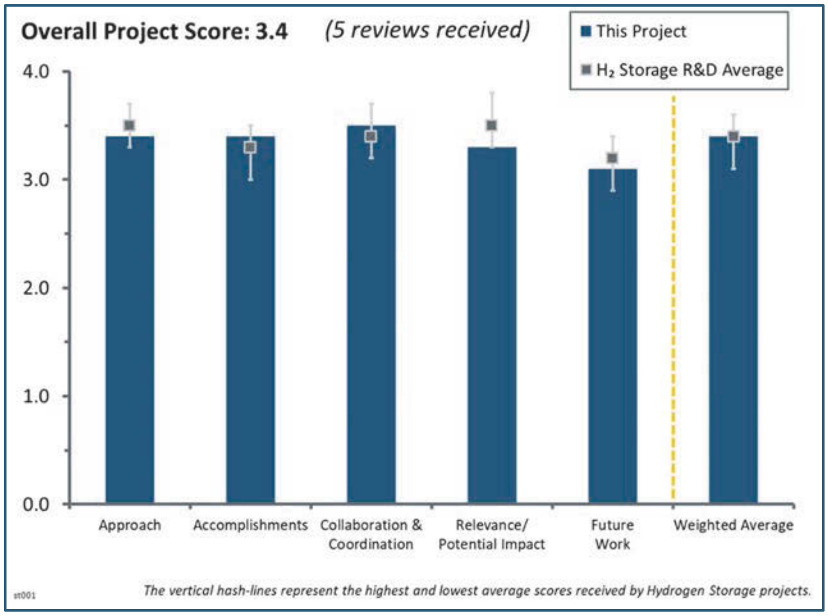
- The catalyst development seems to be rather straightforward. The chemical reactions were under research for a long time; the proposed catalysts (mainly TiO_2 doped with precious metals) seem to be appropriate, but as they contain precious metals, there should be a search for alternatives.
- The project has an enormous scope and is not sufficiently funded to achieve all its objectives. The materials discovery work in Level 1 seems rather simplistic in terms of identifying new options, but perhaps that is just because the methodology and prior work are not adequately covered. While not necessarily a weakness, the project is quite different from other HydroGEN consortium projects, which consist of far more fundamental materials discovery/screening activities.
- The project should strive for more inter-level interaction and integration; the project seems a bit disparate. One of the major advances, the process flowsheet innovations, is dependent on external technology—it might be good to fold that into the project. The project needs to further examine and focus on catalyst development; the team should at least be considering non-Pt materials for catalysts. Further work on characterizing the fabricated material morphology before and after implementation is necessary.

Recommendations for additions/deletions to project scope:

- If this has not already been done, the catalyst discovery work should perhaps be expanded to explore a wider suite of materials. This would provide a better fit with HydroGEN/EMN. The other activities should continue, but additional funding will need to be scrutinized on a cost–benefit basis.
- The project/scope should be expanded to include a more direct interface with the electrolyzer development. This seems critical, as it effects the overall system, and changes in operating conditions enable large changes in process flow. The catalyst scope should also be expanded to include a more fundamental understanding of catalytic behavior and the identification of a novel, less Pt-intensive catalyst.
- The project team should take into account catalysts without precious metals. A closer link with other projects that follow a more theoretical approach toward material description might also add value to the work.

Project #ST-001: System-Level Analysis of Hydrogen Storage Options

Rajesh Ahluwalia; Argonne National Laboratory



Brief Summary of Project:

The main objective of this project is to develop and use models to analyze the onboard and off-board performance of physical and materials-based automotive hydrogen storage systems. Specific goals include (1) conducting independent systems analysis for the U.S. Department of Energy (DOE) to gauge the performance of hydrogen storage systems, (2) providing results to materials developers for assessment against system performance targets and goals and for guidance in focusing on areas requiring improvements, (3) providing inputs for independent analysis of onboard system costs, (4) identifying interface issues and opportunities and data needs for technology development, and (5) performing reverse engineering to define material properties needed to meet the system-level targets.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This is an ongoing project that DOE has relied upon to provide a detailed and meaningful systems-level analysis of hydrogen storage needs and options. The approach is focused on a critical analysis of off-board and onboard targets as well as requirements for materials properties and system configurations. The approach in fiscal year (FY) 2017 and 2018 addresses system-level issues affecting the development of compressed storage tanks (including cryo-compressed hydrogen [CcH_2] storage), hydrogen storage in sorbent materials (including sorbents containing metal cations capable of binding multiple hydrogen molecules on a single site), and (new) hydrogen carriers for hydrogen distribution and transport to the forecourt. The approach is rational and straightforward, and it has provided a means of rapidly and effectively assessing material requirements and properties as well as overall system performance.
- The development of thermodynamic and kinetic models of processes in physical, complex metal hydride, sorbent, and chemical hydrogen storage systems is a very broad and complex approach that touches on key modeling needs. It was not addressed in the presentation, but the finite element analysis for compressed tanks should (and likely does) include properties of materials at relevant cryogenic temperatures.
- The Argonne National Laboratory (ANL) systems analysis project continues to serve a valuable role by independently assessing design variations and engineering features for diverse hydrogen storage systems and materials. This year's assessments of 500 bar CcH_2 storage for buses and light-duty vehicles clearly demonstrate the feasibility of this method for these applications. The evaluation of requirements for room-temperature (RT) adsorption candidates also indicates that there are no known systems that can reach even 50% of these properties. Hence, there seems to be little reason for further exploration of these materials.
- The project has a good history of focusing on the key barriers for hydrogen storage systems using a systematic performance analysis. This year, the project review seemed to include several slides that focused on cost rather than performance; this was confusing, since cost has not been within the scope of this project

in the past. The project has a very good approach to conducting analytical simulations, although it lacks discussion about the validation of the results.
- The project covers a large area of investigation and has presented a large amount of data; however, in all cases, an indication of a path to meet DOE targets is unclear.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Excellent progress was achieved in FY 2017 and 2018 in all four focus areas: cryo-compressed systems, hydrogen storage in RT sorbents, compressed hydrogen storage, and hydrogen carriers for distribution and delivery. The analyses provide a quantitative and detailed assessment of requirements and performance needs in all FY 2017 and 2018 focus areas. This information assists DOE in planning for the Hydrogen and Fuel Cells Program (the Program) and provides a solid foundation for establishing the efficacy of new storage system technologies. The work on cryo-compression systems extends the studies conducted in the last two reporting periods, and it shows that CcH_2 provides clearly superior performance compared to Type 4, 700 bar RT compressed tank storage for fuel cell buses and light-duty vehicles. A particularly noteworthy and timely result concerns the requirements for a sorbent material to meet the DOE storage targets (slide 14). The results indicate that even if four H_2 molecules per metal cation are adsorbed in a (yet to be synthesized) uranium iodide-oxygen (UiO) metal–organic framework (MOF), the absolute uptake is *still* a factor of two lower than the DOE target. The work in the new area of hydrogen carrier development was also impressive because it provides a solid and quantitative systems-level foundation for the technical effort on hydrogen carrier materials efforts that are under way in the consolidated Hydrogen Materials Advanced Research Consortium (HyMARC).
- The project has shown accomplishments in various areas in hydrogen storage systems analysis. The most significant accomplishment was related to the reverse engineering of the material properties for the RT adsorbents. This work was very helpful in aligning the materials research to the DOE system targets. It is also helpful for this project to continue to pursue opportunities to reduce the cost of the 700 bar compressed tank design.
- ANL analyses indicate that the performance levels of existing storage approaches have now reached a maturity level at which only minimal enhancements look likely, with nearly zero-sum tradeoffs between performance and costs.
- The project team needs to assess the impact the modified end cap may have on the overall lay-up, fiber-winding process, and associated costs in tank manufacturing. The project may require changes in the winding pattern that affect cost. It is uncertain why the project team did not assess the potential for 700 bar ambient temperature tanks for use in buses. When asked, the presenter made a reference to Toyota's use of 700 bar tanks, but an analysis of these tanks in buses (if it has indeed not been done previously) is still important. In the "H_2 Carrier Study," it was good to see this particular activity, approach, and related accomplishments. An analysis of the scalability of the three options (C_cH_2 at 350 bar, C_cH_2 at 500 bar, and compressed H_2 at 350 bar) is important for understanding the influence they have on versions of infrastructure and renewable versus non-renewable sources; the analysis should be added to this activity. In addition, glass microspheres were studied for large-scale transport of hydrogen at about 11% gravimetric density, but at about 20 kg_{H2}/m^3 volumetric density. They can be used as one-way or two-way RT carriers. The project received positive Program Annual Merit Review results in the mid-1990s, but it was halted. The project team may be worthy of addition to this study.
- This project covers different methods for onboard hydrogen storage, but it is mostly being compared to 700 bar compressed hydrogen storage. The project does not make clear reference to DOE goals or how the project is expected to progress toward those goals. Compressed hydrogen vessel analysis with boss-reinforced dome finite elements shows the boss plastically deforming under normal operating conditions. It is unclear whether there was an analysis performed to show fatigue durability of the boss component.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- The ANL team continues to interact closely with a variety of other organizations in both government and industry on key aspects of hydrogen production, storage, and delivery. The team remains effective in consolidating the relevant technical inputs and communicating outputs to project partners.
- Extensive collaborations are in place with multiple national laboratories and other research and development (R&D) centers. The collaborations are well managed and coordinated, providing important input to the analyses being conducted within this project. It will be important to enhance the collaborations with the consolidated HyMARC team. The HyMARC project and associated seedling activities have become the focal point for understanding sorption properties and behavior in the most promising storage candidates. It will be essential to augment collaborations between this system-level effort with HyMARC to provide DOE with a complete and fully transparent assessment of the hydrogen storage system status, as well as any challenges.
- The data shared appear to come from a variety of sources, including industry and other national laboratories.
- It looks like this project contains a very good mix of collaborators.
- The project appears to have a high level of collaboration and has been open to reviewing the analysis assumptions. The collaboration list includes several national laboratories and DOE tools, although the industry connection is limited and could be expanded to confirm the results and research direction. The cost analysis collaboration should be further explained, especially in relation to the hydrogen carriers.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project continues to be critical to the success of the Program. It is an ongoing activity that builds upon prior solid successes. This project serves as the definitive source for systems-level analyses and projections for the Program.
- While it is also the greatest challenge, the potential impact of sorbents (especially RT sorbents) is huge if it is successful. This is an iconic example of what government does best that industry and markets cannot do.
- The project includes a mix of relevance and impact based on various applications. The RT adsorbent reverse engineering is highly important for this materials-based storage approach. The impact of the hydrogen carriers was not clearly explained and may have lower relevance.
- The ANL team confirmed that CcH_2 storage systems do very well meeting the onboard targets; nevertheless, there remain significant issues with the necessary liquid hydrogen infrastructure. As the ANL project showed this year with the assessment of the RT adsorption materials, there are no known solid storage media candidates that can simultaneously satisfy the updated 2020 DOE targets, let alone the ultimate values. All candidate storage options exhibit compromises of contradictory requirements and behavior for physical or chemical storage systems. The latest assessment reveals that minor improvements appear to be possible.
- Data within this project is focused on comparison to compressed hydrogen in most areas. There is no clear path to improvement for current technology in some areas of the presentation. Identified barriers such as life-cycle assessment and charge/discharge rate are not addressed in all areas of investigation.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work appears to be a continuation of the past year's activities with limited new areas of analysis. It is good that the future work includes verification of the RT sorbent with Lawrence Berkeley

National Laboratory, along with other sensitivity analysis. The work associated with expanding compressed hydrogen to medium- and heavy-duty fuel cell electric vehicles is an excellent focus.
- The proposed future work follows naturally and directly from prior studies. Work planned in all topic areas is clearly delineated. The future work will establish definitive system requirements and storage/carrier scenarios that will provide important benchmarks for the materials development efforts.
- For the "hydrogen carriers for delivery" section, it is recommended that the team add specific activities for analyzing hydrogen carriers that favor the transition to large-scale renewable resources. Atmospheric nitrogen for ammonia is a renewable resource.
- The tasks outlined by the ANL team are all reasonable and focus on the continuation and extension of the team's current efforts. The scope of work will be useful; however, it seems unlikely (in light of progress and behavior of currently identified materials) that breakthrough discoveries will be made as a direct consequence of this project.
- Future work does not give a clear indication of how progress toward DOE goals will be made.

Project strengths:

- Over the past decade, the ANL team has developed and adapted a diverse variety of models to predict both attributes and limitations of nearly all types of hydrogen storage systems. The team continues to provide useful insights on the constraints required from various storage media in order to meet DOE targets. The team's in-depth analyses are always performed systematically and include inputs and critiques from other organizations.
- This project provides system analyses that are vital for assessing the current state of hydrogen storage technologies and materials development. The results generated in this project provide a valuable "reality check" for materials and system developers.
- Individuals involved in this project have extensive backgrounds in analyzing hydrogen storage systems. In addition, the project analysis often includes a sensitivity assessment to determine the preferred operating conditions.
- This project addresses multiple storage technologies, both onboard and off-board, and identifies base cost and volumetric and gravimetric densities for each technology.
- This project consists of solid teams, solid collaboration, and a strong mix of timely and relevant R&D for hydrogen storage.

Project weaknesses:

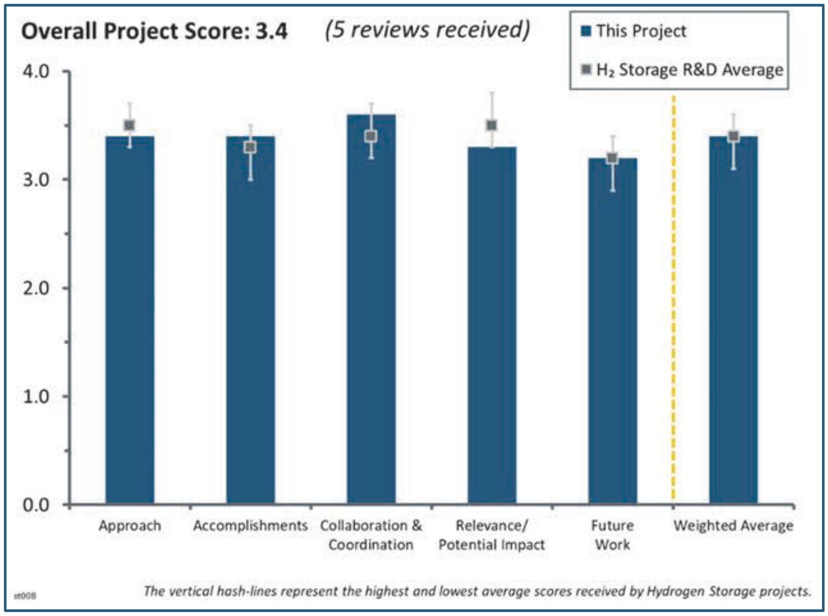
- This is a very strong project with few deficiencies or weaknesses. The only (minor) concern is that a more robust collaboration with HyMARC is necessary. The results of the system analyses should be coupled more strongly to the work on materials development, characterization, and foundational understanding to ensure that the large parameter space for those efforts can be narrowed and distilled in a rational way.
- The project could be improved by reaching out to industry for confirmation and verification of results. The analysis performed in this project is often strong, while the confirmation and cross-reference of results could be further explained. It is assumed that the project individuals are confirming their results in the background, which should be mentioned during a review of the results.
- While the ANL team carefully evaluated detailed aspects and variations of hydrogen storage systems and supporting infrastructure, there have been limited design and materials advancements on hydrogen storage technology in recent years. Hence, the prospects for meeting the major improvements necessary for achieving the DOE targets are being affected. Furthermore, the ANL team neither possesses nor has direct access to a means of validating findings. If outside researchers or industry does not provide these necessary measurements, the refinements or modifications to the ANL findings will not be critically tested; thus, recommendations would not implemented.
- Hydrogen carrier pathways involve hydrogen during the production of the carriers, carrier transport, and hydrogen evolution from carriers, with very little information regarding hydrogen storage. The hydrogen carrier efforts, while critical to hydrogen and fuel cell success, should be moved to a different or separate activity.
- The next step to make progress toward DOE targets is not clearly defined.

Recommendations for additions/deletions to project scope:

- There are no recommendations for changes to the project scope. However, at some point in the not-too-distant future, it is anticipated that the work on tanks and cryo-compressed storage will reach a point at which the emphasis can be shifted more strongly to other candidates that have the potential to supplant the compressed hydrogen approaches.
- One recommendation is for the team to complete reverse engineering for all materials-based storage systems and publish a complete summary table of these targets. It would be helpful to include additional industry feedback regarding certain analysis concepts. For example, bus manufacturers are focused strictly on the cost and robustness of the storage technology; they are not concerned with volumetric density, so cryo-compressed storage may be less interesting, especially if the technology has a high cost penalty for initial low-volume market entry.
- The project team needs to conduct an evaluation of solid storage as a possible carrier for delivery. For various liquid hydrogen carriers, it is unclear what the environmental effects (off-gas) are for each of the evaluated methods. The comparison of Type 3 tanks versus Type 4 tanks at different storage pressures has already been conducted in the past; it is unclear how this will help with progress toward DOE targets.
- It is recommended that the team consider exploring the use of high ZT or other materials for the thermoelectric cooling of the cryogenic-pressure hydrogen tanks. When first explored in 1993, there were no reasonable costing choices, but recent improvements for thermoelectric cryogen applications may dramatically extend dormancy.
- It is recommended that the ANL team be supported to perform all of the tasks summarized in the future plans.

Project #ST-008: Hydrogen Storage System Modeling: Public Access, Maintenance, and Enhancements

Matt Thornton; National Renewable Energy Laboratory



Brief Summary of Project:

The ultimate goal of this project is to provide and enhance publicly available materials-based hydrogen storage system models that will accept direct material property inputs from materials developers to accurately predict materials-based hydrogen storage system performance. In support of that goal, this project maintains, enhances, and updates the Hydrogen Storage Engineering Center of Excellence (HSECoE) hydrogen storage system modeling framework and model dissemination web page.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This project is an extension of the analysis and modeling efforts conducted during the former HSECoE. In particular, this project addresses materials and system issues for alternative hydrogen storage media (e.g., metal hydrides, chemical hydrogen, and adsorbents). Analysis tools were developed and made available to allow outside users in the international hydrogen research and development community to make comparisons over a range of parameters and operating scenarios against reference materials. The objective is to assist material researchers to identify viable candidates with the potential to meet the U.S. Department of Energy (DOE) vehicle performance targets. The project also provides a level of technical support to the model website to assist outside users.
- The approach focuses on the development, validation, and dissemination of modeling tools that can be used to evaluate performance of new hydrogen storage materials in practical storage systems. The focus of the approach is to provide a straightforward and rational way to transfer the engineering development knowledge derived from the HSECoE consortium effort to materials researchers. The project is providing the hydrogen materials development community with the ability to input material properties and to evaluate the impact on system characteristics. Overall, through development and application of a wide range of simulation/modeling tools, the project is ensuring that the HSECoE models are managed, documented, and disseminated effectively.
- The goal of this project is to increase storage materials researchers' ability to use available modeling where there is an impedance match between materials research data and the technical targets for vehicle hydrogen storage systems. The approach was to improve the framework modeling with improved utilities so that research data are directly used to provide evaluations for the materials used in vehicle applications. In the process of improving the modeling, the user interface and website were also improved.
- The tools on the website provide excellent resources to evaluate various storage technologies and have added functionality, allowing users to evaluate most materials based on desired editable inputs.
- The project has a very good approach in developing and making available models for materials-based hydrogen storage researchers, although the project should also utilize its own models to assist in evaluating materials research. For example, the project could conduct a reverse engineering evaluation of the materials research targets using the system models.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Solid progress has been achieved in several areas:
    - Access to/support for the website has been improved.
    - Stand-alone system design tools that facilitate user input on material characteristics in a straightforward way have been developed—specific design tools and system estimators have been developed for metal hydride systems, sorbents, and chemical hydrogen materials.
    - A generic user interface (GUI) for a hydrogen vehicle simulation framework, and the integration of the design tools within that framework, has been demonstrated. Website analytics are being applied to evaluate user access.
- Substantial progress was made during the past year or so in updating, refining, and maintaining the HSECoE model dissemination website. While such simulations are helpful tools in understanding behavior for generic storage media and systems, they do not necessarily hasten discovery or development of the targets. The team spent considerable effort in improving support documentation and making other changes to the formatting and approach to enhance the website's usefulness. The development and implementation of stand-alone system design tools, an isotherm fitting tool, and a new GUI/framework are commendable. These activities make this website a better and more attractive resource for independent research groups.
- The models available cover the range of storage materials and technologies for relevant hydrogen storage systems. A few are in progress, but it appears that they will be completed by the end of the project. The improved website and GUI should help hydrogen storage materials researchers use this valuable utility in growing numbers over time.
- The completion and updates of the stand-alone system design tool models are very useful and an excellent accomplishment. The improved website access and support also improve the modeling effort.
- The project team met the intent of the project, providing tools for evaluation of various storage technologies.

Question 3: Collaboration and coordination

This project was rated **3.6** for its collaboration and coordination with other institutions.

- The technical interchanges among the team members from the different national laboratories, as well as outside members, remains very efficient and highly coordinated throughout this project. The progress made on both the adsorption and metal hydride storage models indicates excellent cooperation. The team reached out to model users via a survey with some follow-up and revisions.
- Beneficial collaborations and cooperation among team members from Savannah River National Laboratory, Pacific Northwest National Laboratory, and National Renewable Energy Laboratory are evident. Additional collaborations with universities, industries, and a private consultant have accelerated progress on the project. The project is well managed, and effective coordination among team members and other collaborators is apparent.
- The collaborators in this project have the key capabilities needed to meet their respective responsibilities. The coordination and management of the collaborations seem to be effective enough to allow the accomplishments over the last three years.
- The project partners are highly collaborative and coordinated in their efforts to develop models. The validation of the models needs to be further evaluated with external researchers. The idea of conducting a survey was good, although the use of the results to further collaboration with the users is uncertain.
- There is good collaboration with other national laboratories. More verification of results from industry is suggested.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project ensures that models developed and tested in the HSECoE consortium and elsewhere for evaluating storage materials relative to DOE targets are codified and disseminated to the materials community in a user-friendly and capable format. This project is extending and augmenting the important work that was conducted in the HSECoE. It is an important part of the overall DOE energy research, development, and demonstration strategy and is generally well aligned with the goals and objectives of the Hydrogen and Fuel Cells Program.
- The accomplishments in this project align very well with DOE objectives and should significantly aid in moving toward those objectives. The utility of the modeling system should significantly increase the development rate for materials-based and other hydrogen storage systems for vehicles.
- These good tools facilitate the ability to evaluate different storage technologies and understand the benefits and limitations.
- The project team continues making very good progress in providing very accessible enhanced numerical models that had originally been developed during the HSECoE but have undergone extensive revision and refinement over the past couple of years. Their recent work has made these models more accessible to the general hydrogen storage community. Nevertheless, it remains unclear just how much other research groups are willing or able to fully utilize these tools for assessing progress and determining limitations on meeting the DOE performance targets.
- The project has high relevance as a bridge between materials research and DOE system technical targets. However, the impact of the project is uncertain, since the project is developing the tools rather than using the tools to guide and assist the research directly.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The planned expansion of the model to other near-term vehicle platforms is very important. The optimization of a given vehicle platform for a particular application does not necessarily need the same storage system as a light-duty vehicle for highway use. Adding the vehicle-side refueling model and relating to refueling infrastructure needs would be a valuable addition. All the “Next Steps” proposed plans are important to accelerating vehicular hydrogen storage development and, in turn, helping in the growth of hydrogen as a transportation fuel.
- The team appears well positioned to complete all of the prescribed tasks by the end of fiscal year 2018 (FY 2018). It would be very valuable for the team to maintain the model websites and also provide technical support to outside users. Finally, it is recommended that this project receive continued support to expand the models by applying them to other storage materials, theoretical formulations, and vehicle class options.
- The project ends this year on September 30, 2018. Completing the proposed future work outlined on slide 31 is an ambitious undertaking. The more reasonable work schedule described on slide 30 (i.e., milestones and deliverables) seems straightforward and includes reasonable extensions that could be accomplished by the project completion date.
- The proposed future work is very interesting, especially in the area of expanding to fueling and other vehicle platforms. The plan to accomplish this future work needs further explanation to ensure the effort is focused and containable.
- Validation of the model is critical. Correlation between the model and actual data is key to the acceptance of the results of the models. As a design tool, results will be taken with a level of skepticism until the correlation data is presented. The evaluation of variables that change depending on vehicle class would expand the usefulness of the tools with minimal additional effort.

Project strengths:

- As described in prior reviews, the core team members have extensive knowledge and expertise on all of the hydrogen storage media, as well as the appropriate software analytical packages to develop and execute the modeling codes for the website. This team includes a collection of experienced individuals to continue and extend the storage system parameters.
- The members involved were part of the HSECoE and understand materials-based systems along with materials research attributes. The models are very useful tools for materials researchers and are relatively straightforward to utilize, based on GUI screens and other instructions.
- This is a well-coordinated effort that is ensuring that the results and knowledge gained in the HSECoE effort can be used effectively by the hydrogen storage materials research community. This is an important legacy of the HSECoE.
- This project's organization and project execution are solid, as is the relevance to the DOE goals and the needs for the growth of hydrogen vehicles in the marketplace.
- The project team created good evaluation tools with clear definitions and flexibility to allow users to evaluate various materials and storage technologies.

Project weaknesses:

- This is a strong technical team with diverse expertise; hence, there are few weaknesses associated with the team's ability to develop and deploy the analytical tools. The primary limitation is the absence of validation results and feedback from outside users.
- There are many incomplete tasks ahead with only three to four months of the three-year project time and 14% of the budget left. If expansion of materials models expects researchers to provide specific technical data on their materials, it is unclear what will motivate them to provide that information.
- The main project weakness is that the models are being developed but are not being utilized to make projections or develop strategies for closing the gap to the DOE hydrogen storage system targets. Also, the validation of the models should be further explained to allow researchers to gain confidence in the results.
- Validation of the models continues to remain a dominant issue. Greater emphasis is needed on a more detailed description of the approach for validating the models and design tools.
- Correlation data between models and real life are desired to validate the models. Having more data on the website showing this correlation would be desirable.

Recommendations for additions/deletions to project scope:

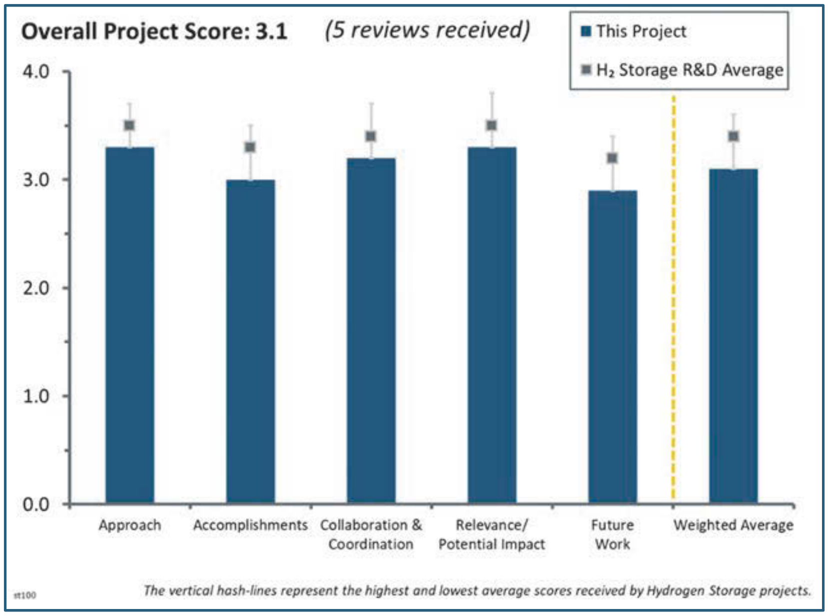
- Since the project is apparently essentially complete with respect to the planned analytical models, the planned final additions are satisfactory. However, funds should be made available for at least another year or longer to maintain the models on the Internet and also support appropriate team members to respond to user inquires. It is recommended that this project be extended to allow the team to expand the model platforms to other fuel-cell-powered vehicle types (e.g., medium and heavy-duty trucks, forklifts, buses, etc.).
- The project should include the scope of using the models to develop strategies and provide sensitivity analysis of key materials attributes to achieve the DOE system targets. The project team should assess the level of interest and downloads for certain models and develop a plan regarding the deletion of support for certain models based on the interest level. Overall, the project team should attempt to increase the usage of the models through various communication approaches to connect with materials researchers.
- Use of the website by industry has been quite limited; this may be due to industry's not knowing of it. Links to this website from other locations (e.g., DOE, California Fuel Cell Partnership) could help people find the site and increase the benefits of the work completed.
- This project is concluding this year on September 30, 2018. There are no additional recommendations for changes in the project.

Project #ST-100: Hydrogen Storage Cost Analysis

Brian James; Strategic Analysis, Inc.

Brief Summary of Project:

The goals of this project are to (1) conduct independent Design for Manufacture and Assembly (DFMA) cost analysis for multiple onboard hydrogen storage systems and (2) assess/evaluate cost-reduction strategies to meet the U.S. Department of Energy (DOE) cost targets for onboard hydrogen storage for light-duty fuel cell electric vehicles.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project team's DFMA-based cost analysis approach provides rational and meaningful component and system cost analysis predictions and is useful for identifying optimum cost design and manufacturing pathways. The approach has been proven effective in prior studies, and optimization of the approach provides important new cost analyses that are helping to inform decisions for the DOE Hydrogen and Fuel Cells Program (the Program). The focus in fiscal year (FY) 2017 and 2018 was on the analysis of light-duty vehicles (LDVs), fuel cell electric buses (FCEBs), and Type IV natural gas storage systems. These analyses directly complement those conducted in the companion systems analysis project led by Argonne National Laboratory (ANL) (ST-001). The reverse engineering of metal hydride (MH) systems was an important addition to the overall project scope for this reporting period.
- The project work is focused on the cost of hydrogen storage systems, which is the most critical barrier for the commercialization of these systems. The activities within the past year include a very good balance between LDVs, bus applications, and compressed natural gas (CNG) analysis. It was excellent that the project team utilized its cost estimation tools to conduct a reverse engineering approach with MH. This approach should be extended to other hydrogen storage systems. The approach of extending to CNG examples is helpful in order to evaluate a similar technology.
- Strategic Analysis, Inc. (SA) uses well-established analytical tools and detailed descriptions of the various hydrogen storage systems to explore the impact of design choices and materials selection on the cost of representative configurations. Systematic assessments were made to ascertain relative roles of specific components on both performance parameters and costs. One limitation is the absence of commercial validation of projections and findings.
- The project team looked at five different storage systems and derived potential costs and cost sensitivities. The use of DFMA as the primary method for defining manufacturing costs should lead to reliable predictions of costs and sensitivities. The reversible MH system design and analysis were straightforward and reasonable, and the results are probably realistic. It is a useful foundation for sensitivity analysis of potentially practical vehicle hydride storage system designs and MH material choices. For composite pressure vessels, a comparison between wet lay-up fiber winding and advanced tape placement (ATP) was done to look at cost drivers for both methods for composite overwrapped pressure vessels. It is uncertain that the collaboration with DuPont provided reliable data to develop a reasonable cost comparison. It seems to be a little ambiguous at this point. It is uncertain that this activity shows much future programmatic value.

- This project consists of a general coverage of current technologies and reasonable estimates of technology costs. ATP costs and speed are the same as those for wet lay-up. Typically, ATP is slower in speed and its materials more expensive than wet winding; it is necessary to verify those numbers.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Solid progress was made in FY 2017 and 2018. Most notably, the comprehensive MH reverse engineering work successfully identified parameters that could be altered/optimized to meet cost targets. A manufacturing process flow comprising elements unique to MH storage systems was developed, and an analysis of thermodynamic constraints on cost projects was performed. This analysis is necessary for a rational and sensible assessment of the MH system and its manufacturing cost. A similar process flow analysis was performed for a CNG storage system. In this case, the analysis focused principally on the manufacturing approach. This analysis facilitated a formulation of tank cost comparisons and the evaluation of primary cost-critical components and processes. Cost analysis for storage options in FCEBs was focused on a 500 bar cryo-compressed system. Useful results and conclusions concerning costs of specific steps and components in the process flow and comparisons with conventional compressed gas storage were presented. As an aside, on slide 10, it seems that the "ship in a bottle" approach to the assembly of the MH heat exchanger begs the following concern: if the heat exchanger fails, it is unclear whether it can be swapped out or the entire assembly needs to be replaced. That could be a costly and time-consuming proposition.
- A key accomplishment of the project is the reverse engineering effort, since it concluded that the DOE target cost is not attainable with the MH concept. This important result can be used to influence the MH research strategy and targets. The 700 bar system baseline updates were also useful in evaluating attribute tradeoffs to improve the cost.
- With the exception of the wet lay-up versus ATP study, the project's accomplishments this year all represent progress toward the Program's Hydrogen Storage R&D category goals. The 700 bar baseline updates provide interesting insight into a number of things, in particular, the regulator pressure drop decrease and relaxed fuel cell system requirements. The latter implies the need for an additionally interesting trade analysis iterating different fuel cell/regulator configurations versus drive cycles. The FCEB cryo-compressed versus compressed hydrogen analysis is valuable in showing the best current-application benefit from transitioning to cryogenic fuel infrastructure and cryo-compressed vehicular storage.
- During the past year, the project addressed four primary topics: (1) revised costs for 700 bar Type IV hydrogen gas storage in LDVs; (2) reverse engineering analysis of hybrid 350 bar reversible MH systems based upon a Type IV vessel; (3) cost analysis of the 500 bar (60–80 K), cryogen-compressed hydrogen (CcH_2) storage systems for FCEB applications that had been previously conceived by Lawrence Livermore National Laboratory (LLNL) and evaluated by ANL; and (4) Type IV tanks for a 3600 psi CNG storage system. The purpose or rationale for evaluating a CNG system within the Program is not clear, other than to provide some independent validation of the assumptions for commercial materials and manufacturing costs on the SA analysis methodology. Furthermore, the selection of a Type IV hybrid MH tank is very ill advised because the polymer liner is highly vulnerable to damage from the expanding and contracting hydride particles; this would generate excessive hydrogen permeation and leakage via generated defects, and the outgassing of volatile organic species from the polymers over time and during temperature excursions would likely contaminate the hydride material. This, in turn, would seriously impede kinetics and storage capacities and would form impurities in the delivered hydrogen gas. Only metal inner liners should be considered for vessels containing MHs.
- This project successfully evaluated the costs of leading technologies and identified issues and possible solutions for technology shortcomings. The cryo-compressed data references ANL with no new data presented, thus not providing independent analysis for this technology.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- Collaborations with national laboratories (Pacific Northwest National Laboratory, LLNL, and ANL) facilitated and enhanced the technical effort within this project. The collaboration with ANL is especially noteworthy because the ANL systems analysis efforts provide important and timely input to the cost analyses in this project. In addition to the national laboratory collaborations, more active participation of industry partners is being sought and encouraged.
- The project team has direct collaboration with national laboratories and industry to assist in confirming assumptions and reviewing the results of the team's analysis. The project's proactive communication with technology stakeholders to direct and review the team's analysis is a key strength of this project.
- The collaborators and their roles are defined and appear to be well managed for the goals of this project.
- The presentation lists a wide group of national laboratories and industry that have collaborated on this project.
- SA has cooperated closely with ANL on many aspects of the analyses and also gathered information and input from a number of independent organizations on various aspects of hydrogen storage media and methods. However, the team apparently had only limited contact with organizations that had hands-on experience with intermetallic and complex hydrides prior to assessing the high-pressure hybrid storage vessels.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project, in tandem with the ANL systems analysis project, provides DOE with quantitative and comprehensive technoeconomic analyses and technical status and projections for hydrogen storage systems. The DFMA analysis employed in this project has been shown to be effective for predicting the costs of manufacturing processes, materials, and components. DOE uses this information to inform system and manufacturing development decisions. Overall, the project is well aligned with the objectives and goals of the Program.
- The project has high relevance, especially since cost is a key barrier to the commercialization of hydrogen storage systems. The project not only identifies the cost but also attempts to identify solutions—although further work could be conducted to cascade cost goals and opportunities for certain system elements in order to achieve the targets.
- Excepting the ATP versus wet lay-up, all the projects in this effort meet the needs of the Hydrogen Storage R&D category and are helpful in moving the bar for hydrogen vehicle storage systems.
- This project contains the cost analysis of leading hydrogen storage technologies and helps to identify areas that prevent these technologies from reaching DOE targets.
- The independent, yet coordinated, assessments by SA are valuable to the development of cost-efficient hydrogen storage systems. The concern is that without validation from actual vehicles and fabricated systems, these analyses will emphasize minor (rather than unanticipated major) issues.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed future work is a reasonable and rational extension of the technical direction established in the prior year. The addition of metal–organic framework (MOF) reverse engineering analysis (complementary to ANL systems analysis) is important.
- The proposed future work appears to be a continuation of the past year's activities, rather than new activities to advance the technology. The only new item was the MOF reverse engineering analysis, which would be very useful. The project team should review the future work plan and modify it to include higher-

impact analysis of options to improve the 700 bar baseline system for the tank, rather than the regulator, since the tank has the highest cost contribution. The cryo-compressed cost estimates should be validated by original equipment manufacturers that have produced these systems, since the cost projections do not seem to align with the current actual costs.

- Analyses of the high-pressure MHs should consider Type III vessels rather than Type IV designs. Since adsorption systems have considerable temperature excursions during operations, analyses should consider the impact of cryogenic temperature on the mechanical properties of carbon and polymers. Unless stronger justification can be provided by SA, there seems to be only limited purpose for continuing the CNG cost and design analyses.
- The extrapolation of ATP translation efficiency from 3600 psi containers to 700 bar containers needs to be verified for this data to be usable. The recyclability of a vessel is a desired benefit for society, but it is not typically a cost-saving measure for vehicle manufacturers or primary customers, as recycled fibers cannot be used in vessels at this time.
- It is important to continue all the LDV and FCEB plans as listed. The FCEB analysis should coordinate with some fueling infrastructure analysis. Continuing the Type IV CNG analysis does not appear to seriously move toward DOE storage goals.

Project strengths:

- The focus of this project and the individuals involved in the analysis are both strengths of this work. The focus of the project deals with cost, which is the key barrier to hydrogen storage commercialization; this is the only project in the portfolio dealing with cost. The individuals conducting this analysis have excellent capabilities and are transparent with the assumptions and results.
- A well-formulated approach, conducted by a highly capable engineering team, is being used to generate important information concerning the optimization of the manufacturing process flow and the cost of materials and components. The information has important impact on storage system development decisions.
- The SA staff have an excellent grasp of the analytical methodology and computation models on assessing costs for a wide array of hydrogen storage systems. The team clearly communicates the findings and implications of these evaluations.
- This work has a good use of DFMA techniques. The management and collaboration appear to be project strengths. The results of current and future FCEB analysis could strongly influence the advent of better hydrogen bus fleets.
- This project's strengths lie in its independent cost analysis of technologies and the identification of cost barriers that need to be overcome.

Project weaknesses:

- A minor weakness of this project is that a "Summary Slide" would have been helpful; one should be included in future presentations. In addition, the dominant challenges, obstacles, and risks to achieving the project objectives (and meeting DOE requirements) should be stated clearly and candidly. Without that information, it is difficult to fully assess the overall status and future direction. Finally, closer ties to the consolidated Hydrogen Materials Advanced Research Consortium (HyMARC) should be established. Although the cost analysis activity does not fall within the purview of "foundational understanding," it is important for the principal investigator and his team to be fully aware of new and recent developments in the hydrogen storage arena.
- Without actual in-house hardware engineering and materials characterization experience, unrealistic and risky selections have been made on candidate configurations and manufacturing approaches for hydrogen storage systems. This issue could be addressed by more extensive interactions and consultations with organizations and individuals with the appropriate expertise.
- Cryogen-compressed data appears not to be independent. The evaluation of this technology is weak. Technology improvements discussed in the new baseline are not evaluated for further reduction for compressed hydrogen by compounding possible reductions.
- The project team's weakness is the inability to verify the results. These results may appear optimistic in comparison to actual industry costs owing to comparing price versus cost information.

- The ATP versus wet lay-up activity is well executed, but the value versus cost of the activity is unclear.

Recommendations for additions/deletions to project scope:

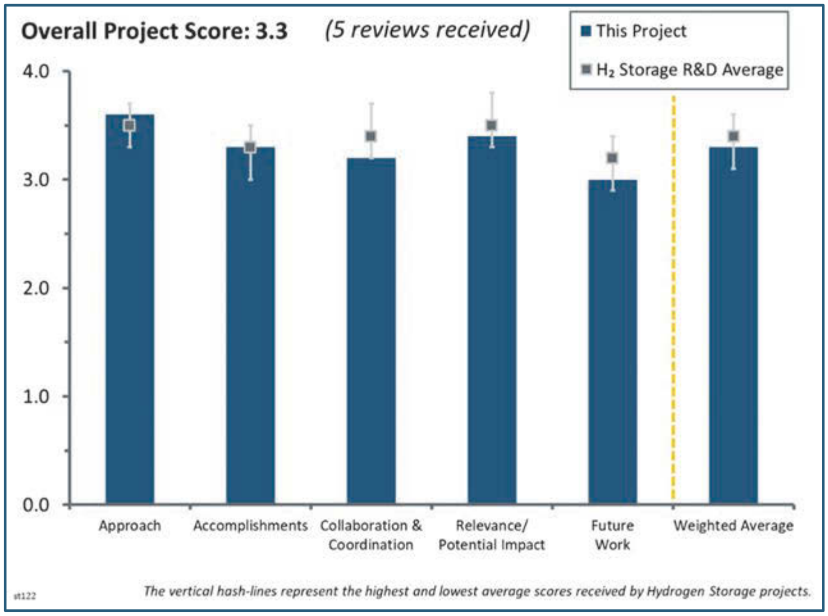
- It is recommended that the team continue and expand the reverse engineering effort to establish goals for materials costs and other system elements. The project scope should be modified to focus on the highest-cost contributors (such as the 700 bar tank), rather than smaller items (such as the regulator). Additional low-volume cost estimates for the storage system would be useful. The consistency of the cryo-compressed cost analysis should be confirmed for low volume to ensure the initial introduction of these technologies could be implemented without a significant cost penalty.
- If the FCEB CcH2 versus compressed hydrogen sensitivity analysis is to be finalized, it should be accompanied by the initiation of a cost analysis for the fueling infrastructure differences between 350 bar compressed and 350/500 bar CcH_2. This is because bus fleet applications, like materials-handling operations, are fleet-like, self-contained, and require concurrent installation.
- Revised analyses of the 350 bar MH should be done on Type III vessels instead of completing assessments of the Type IV configurations. It is recommended that the team cease work on the Type IV CNG analyses and devote more time to other topics or decrease the scope of this project.
- The balance of plant (BOP) evaluation was done only for the regulator. It is suggested that the team possibly evaluate other BOP components for additional cost reductions.

Project #ST-122: Hydrogen Adsorbents with High Volumetric Density: New Materials and System Projections

Don Siegel; University of Michigan

Brief Summary of Project:

A high-capacity, low-cost method for storing hydrogen remains one of the primary barriers to the widespread commercialization of fuel cell vehicles. Storage via adsorption is a promising approach, but high gravimetric densities typically come at the expense of volumetric density. This project's goal is to demonstrate best-in-class metal–organic frameworks (MOFs) that achieve high volumetric and gravimetric hydrogen densities simultaneously, while maintaining reversibility and fast kinetics. The approach entails high-throughput screening coupled with experimental synthesis, activation, and characterization.



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- High-throughput screening combined with synthesis, activation, characterization, and system-level projections is used to identify and test promising MOF candidates for hydrogen storage. The high-throughput screening approach is novel and powerful. It has provided a way to explore a huge parameter space that would be experimentally intractable. It provides useful information for identifying MOFs capable of high gravimetric and volumetric hydrogen densities under cryogenic conditions.
- The principal investigator (PI) screened most of the 500,000-MOF database of databases. The screening is to identify any MOFs with gravimetric and volumetric hydrogen densities greater than the reference, MOF-5. Volumetric density is critical since it is closely linked to packaging issues in the design of vehicles. The 700 bar tank volumetric densities are about as low as tolerable for many light-duty vehicle designs. Once identified, the best MOF candidate properties are used to define relevant storage system designs or characteristics.
- The project has a very good approach by combining (1) a theoretical basis to screen candidate MOF sorbents based upon critical properties that were complemented by synthesis and (2) empirical characterization of the most promising materials.
- The project made important progress between August 1, 2015, and July 31, 2018. The computational screening performed showed good success. Improvements over MOF-5 performance were demonstrated for three cases. The system-level tests were performed, and challenges with increasing usable gravimetric capacity were clearly identified.
- The project goal is to outperform MOF-5 at 700 bar and to pay further attention to volumetric capacity (without sacrificing kinetics). The approaches to meet these goals are clearly laid out as (1) systematic modeling and (2) system modeling.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The identification and synthesis of MOFs with usable capacities exceeding MOF-5, the incumbent material, is a particularly noteworthy result. The scope of the computational effort is stunning. The PI and his team have done a superb job of surveying such a vast parameter space and down-selecting promising storage candidates. These results will serve as an important research benchmark for future work on physisorption materials. However, the obstacles to synthesis of the hypothetical structures remain problematic (desolvation, framework collapse, etc.). The "synthesis bottleneck" is a serious challenge. It may be beyond the scope of this study, but only limited information is provided concerning MOFs that may support metal cations that facilitate binding of multiple hydrogen molecules. This has become the preferred approach and "holy grail" for achieving the highest capacities. In addition, optimal adsorption enthalpies are equally important but received only minimal emphasis (slide 23). It would be valuable to know whether the screening approach can be adapted to include predictions of heats of adsorption.
- Three interesting MOFs were identified and studied. They had significantly higher gravimetric hydrogen densities than MOF-5, but only one exceeded the volumetric density of MOF-5 by almost 15%. Supercritical carbon dioxide (SC CO_2) activation of MOFs is better than vacuum activation of MOFs, but in the magnesium-based Mg-MOF, it resulted in a structure collapse. Perhaps the extraction rate of solvent or SC CO_2 is an issue. Supercritical solvent extraction was necessary for the production of aerogels, and it is possible the extraction rate was an issue in the final structural integrity. The team developed a useful database for MOFs that will be used by others. It is hoped that this project can continue so the lessons learned for things like supercritical activation, system-level optimization, and packing fraction optimization methods will not be lost and instead continue improving the likelihood of identifying the storage material and system that brings hydrogen vehicles to the next commercialization stage. Using the UMCM-9 MOF in Figure 29 (or any other good MOF), it is unclear whether there is enough pore volume when it is compacted to 0.2 g/cc so that changing the pressure from 100 bar to a higher bar (e.g., 200 or 300) has a significant enough change in volumetric capacity to be significantly better than the 700 bar system, or as good as the cryo-compressed hydrogen vessel at 350–500 bar.
- The research has identified IRMOF-20 as one that outperforms MOF-5. Additionally, SNU-70 and NU-100 have been discovered to outperform MOF-5 by 14.1%.
- This project's accomplishments are commendable. The progress toward the goal, however, is intertwined with basic assumptions made in the project. Scientific progress made will be valuable to future researchers. The system-level challenges remain a major road block. Computations led to many more suggestions than can be synthesized or tested. It may be time to rethink high-throughput capabilities for synthesizing/testing such unexplored suggestions.
- Over the past three years, good progress was made that led to viable candidates being identified and examined by volumetric measurements; however, it must be pointed out that none met or exceeded the criteria necessary to achieve the 2020 DOE targets.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- There were excellent interactions within the project among the partners. The most significant external interaction was with the Savannah River National Laboratory on modeling. However, apparently little characterization with either the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) or Hydrogen Materials—Advanced Research Consortium (HyMARC) was solicited or performed; such work would have enhanced this project.
- Solid and beneficial collaborations with Ford Motor Company and the Hydrogen Storage Engineering Center of Excellence (HSECoE) have augmented the core project team's technical efforts. Closer cooperation with investigators in HySCORE (especially J. Long, Lawrence Berkeley National Laboratory) might have accelerated progress.

- This project showed very good and well-coordinated collaboration. There was a great use of organizational capabilities with the University of Michigan, Ford Motor Company, and HSECoE.
- Collaboration with Ford Motor Company was important; however, the rest of the collaboration inside the University of Michigan and with other groups could have increased the net impact of the effort and funding.
- The team collaborates with Ford Motor Company and the HSECoE.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project addresses what the potential is of identifying and discovering adsorbent materials with the highest volumetric and gravimetric capacities for reversible hydrogen storage. Several potentially promising candidates were found and prepared for characterization. These studies are valuable for establishing whether cryogenic adsorption offers viable solutions for vehicle hydrogen storage. However, no candidates were found that allowed ambient temperature storage that exceeds conventional 700 bar compressed gas capacities or would be capable of meeting the DOE targets.
- This is a unique project in the Hydrogen and Fuel Cells Program portfolio. The extensive survey of MOF candidates has provided information that will serve as a useful resource for future research. Although there are many unanswered questions and obstacles, particularly with regard to actually synthesizing the most promising candidates identified in the survey, these results nonetheless provide DOE with important and meaningful new information. The project is well aligned with DOE research and development goals and objectives.
- The potential is high for materials-based hydrogen storage systems with weights and volumes important to using hydrogen as a transportation fuel. Seeking out the right adsorbent materials among likely candidates is critical to long-term hydrogen success.
- New MOFs as sorbents that outperform MOF-5 are being pursued. The shift in idea to pursue high volumetric capacity, rather than gravimetric capacity, forms a unique approach for this research project.
- The relevance of this project is high for the field. The methods developed, if made available, and collaborations established with the broader community of researchers can have a high impact. However, at this point, the impact is limited.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The project is ending July 31, 2018. The proposed future work on evaluating performance characteristics of selected MOFs identified in the modeling work, archiving computational data, and submitting manuscripts for publication seems reasonable in the short time remaining in the project.
- Since this project ends within a few weeks of the 2018 Annual Merit Review, there can be little practical guidance on future work. However, it is recommended that the project's final report fully document the properties of the most attractive candidates, as well as identify any promising screened candidates that either could not be synthesized or had hydrogen adsorption well below the predictions.
- The project is due to end July 31, 2018. If it continues beyond that, the Potential Future Work slide and Challenges and Barriers slide should guide the project.
- The project should provide a summary of factors that enhance volumetric capacity. Systems modeling will be undertaken in the future (in collaboration with the HSECoE).
- No new ideas were proposed to address the main challenges. The ideas listed seem to be some more of the same approach. To be competitive in future rounds of competition, new ideas and new collaborations will be necessary.

Project strengths:

- The project had a strong effort in handling and classifying real and predicted MOFs for their hydrogen storage potential. The approach is solid, and the theory level is commensurate with the goal of screening a large number of potential candidates. The team met some of the goals; some intractable ones remain a challenge in this field.
- The project shifts thought to the pursuit of volumetric capacity for sorbent materials. This has proven successful for this project and will likely spawn additional research in this topic area.
- An impressive survey of the overall MOF landscape and parameter space volumetric and gravimetric capacity performance has been conducted. The vast scope of the survey has provided information that will undoubtedly motivate future work.
- This project is a great foundation for high-throughput screening of hydrogen storage material candidates and for translating data to system-level modeling.
- Extensive screening with the MOF materials group was combined with supporting experimental work on the more promising candidates.

Project weaknesses:

- The "holy grail" for hydrogen storage in MOFs is the identification and synthesis of physisorption materials capable of supporting metal cations that bind multiple hydrogen molecules. This was apparently beyond the scope of the present study. However, it remains the most important and challenging area of study for hydrogen storage in MOFs. It is unfortunate greater emphasis was not given to that issue. In addition, it would have been helpful if the survey could have been linked to an analysis that included predictions of heats of adsorption.
- Perhaps calculations could include a packing fraction estimate subroutine coefficient that can quickly and reasonably determine packability levels of each proposed structure. If it is possible, it would be interesting to know if that could aid in the high-throughput calculations using pelletization or powder packing rather than using crystal densities.
- Assessments were based upon compiled information on only MOF materials; hence, it is highly likely that there were promising candidates overlooked or inadequately considered if data were not available or incorrectly cited. This project appeared to make little use of the potential insights possible from the HySCORE and HyMARC consortia and obtained greater understanding on promising candidates identified during the screening process.
- One project weakness is the very linear attempts at organizing and running this project. Some of the challenges are foreseeable, but no new mitigation approach was developed to address the system-level concerns and underperformance of the gravimetric storage density.
- The researchers are urged to summarize the factors that contribute to high volumetric capacity.

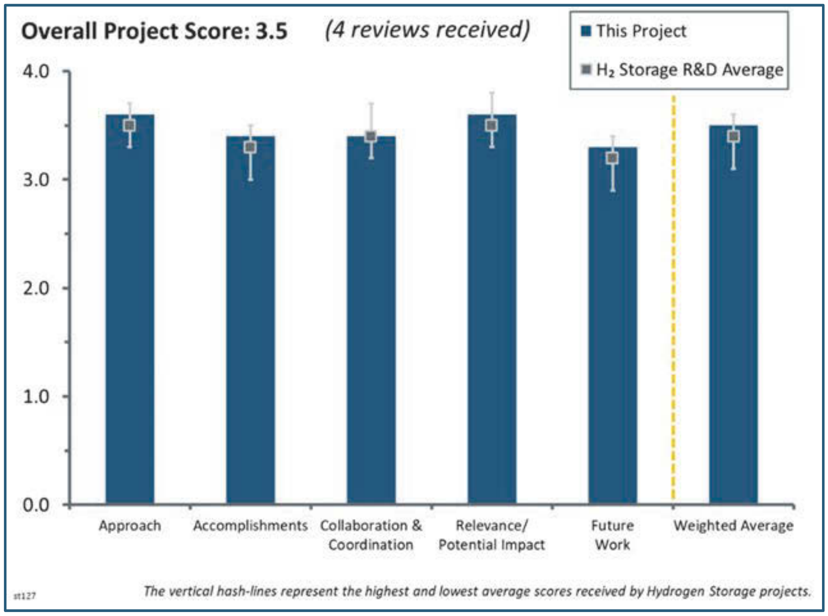
Recommendations for additions/deletions to project scope:

- This project should continue.
- The project is ending July 31, 2018. Therefore, no recommendations are provided concerning revisions to project scope.
- The project is ending. Recommendations for additions/deletions to project scope are not applicable.
- Since this project is now effectively completed, there is nothing more to say.

Project #ST-127: Hydrogen Materials—Advanced Research Consortium (HyMARC): A Consortium for Advancing Hydrogen Storage Materials

Mark Allendorf; Sandia National Laboratories

Brief Summary of Project:



Critical scientific roadblocks must be overcome to accelerate materials discovery for vehicular hydrogen storage. The project objective is to accelerate discovery of breakthrough storage materials by providing capabilities and foundational understanding. Capabilities will include computational models and databases, new characterization tools and methods, and customizable synthetic platforms. Foundational understanding is needed for phenomena governing the thermodynamics and kinetics-limiting development of solid-state hydrogen storage materials.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- Hydrogen Materials—Advanced Research Consortium (HyMARC): The barriers and challenges to onboard hydrogen storage are clearly understood. The approach that has been adopted by the core HyMARC team is comprehensive and focused keenly on the thermodynamics and kinetics issues that limit the performance of reversible hydrogen storage media. An impressive combination of theory and modeling across multiple time and length scales, synthesis and unconventional processing (e.g., very high pressure), and sophisticated in situ and ex situ characterization techniques is facilitating a deeper understanding of fundamental processes that control hydrogen sorption behavior in storage materials. In addition, the HyMARC team is providing excellent support (mainly theory/modeling and characterization) to multiple new seedling projects that are now part of the overall HyMARC effort.
  Hydrogen Storage Characterization Optimization Research Effort (HySCORE): The approach adopted by the HySCORE core team comprises two major elements: (1) development of improved validation measurements and protocols and advanced characterization techniques, and (2) development of improved hydrogen storage materials and creation of a more in-depth understanding of thermodynamics and kinetics operative during sorption reactions in candidate materials. The approach in part (1) is comprehensive and impressive, spanning a wide range of existing and new characterization techniques that have direct relevance to understanding the properties and behavior of hydrogen storage materials. The techniques directly complement the new in situ methods being applied in the companion HyMARC effort. The approach in part (2) focuses on adsorbent materials, mainly carbon-based and metal–organic frameworks (MOFs) and, to a lesser extent, reversible metal borohydrides. The work on development of models and fundamental understanding of thermodynamics and kinetics in those systems is very similar to the work under way in the companion HyMARC. The consolidation of the two consortia will undoubtedly result in more clearly defined roles and objectives and refinement of candidates selected for further study.
- HyMARC has established the analytical tools, models, and teaming methods to quickly increase the information base needed to identify solid-state materials and their behaviors that will be needed to enable

improved hydrogen storage so critically needed for the growth of hydrogen use in transportation. The HyMARC team is clearly going to add to those abilities with this consortium makeup and strategy.
- The overall approach is strong. The combination of theory, modeling, experiments, and characterization is appropriate for achieving HyMARC goals.
- The team is a newly combined HySCORE and HyMARC group. As such, overlapping objectives still exist. Before the next review cycle, it is recommended that the teams define a set of objectives that considers the overlap (as well as the status of the field).

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- HyMARC: Excellent progress was made in 2017–2018 in all core project areas and seedling support activities. Especially noteworthy was the integration of in situ, high-resolution characterization tools (e.g., X-ray photoelectron spectroscopy [XPS], X-ray absorption spectroscopy [XAS], transmission X-ray microscopy [TXM], scanning transmission X-ray microscopy [STXM], inelastic neutron scattering [INS], low-energy ion scattering [LEIS]) into the overall effort. This is providing entirely new and valuable insight in fundamental processes that is being used to directly validate and support the thermodynamic and kinetic models being developed. Likewise, understanding how emerging nanoscale encapsulation structures can be used to effectively confine hydride molecules and clusters is having an important impact on improving hydrogen-sorption kinetics. The results from the theory and modeling efforts are impressive and are providing useful guidance and support for the experimental efforts. The focus of experimental and theory efforts on understanding and improving the performance of metal borohydride systems is providing new insight and paying big dividends. This is a critical area for continued emphasis. The development of an improved understanding of how additives and catalysts alter sorption reaction kinetics and complex hydride systems remains a serious challenge. Greater attention to this important—and admittedly complicated and multifaceted issue—is needed.
  HySCORE: Solid accomplishments and progress toward DOE goals were made in 2017–2018. The extensive effort on development and application of characterization techniques is paying big dividends, and it is providing DOE with important resources that can be used in seedling work and by other collaborators. Impressive progress is being made on the challenging problem of multiple metal site incorporation in MOFs for enhanced hydrogen storage capacity. The work on C_2N and Ca-oxalate is producing intriguing results, but the ultimate payoff remains questionable. The team should seriously consider whether this work should be continued in the expanded consortium activity. The underlying causes of hydrogenation enhancement in boron- and nitrogen-doped carbon remain as outstanding research issues. It is not yet clear if enhancement is caused by actual chemical doping or by defect-mediated processes. Further work is needed to elucidate the detailed mechanism(s). The foundational work on hydrogen carriers conducted within HySCORE will be important in the consolidated consortium with HyMARC. The HySCORE team, especially at Pacific Northwest National Laboratory, provides important chemical insight that will definitely be needed in the future work.
- The accomplishments relative to DOE's goals are extensive throughout the consortium project.
- The accomplishments are being met, and the pace of progress since the last review is impressive.
- The goal to establish in operando probing is within reach but subject to availability of beam time at the facilities. It is an external factor but a predictable challenge. Currently, Li_3N and $LiNH_2$+LiH explored using STXM seem to provide promising results. In general, the STXM method is promising but needs further work to establish this as an established capability. Since not much of it is under the current team's control, some rethinking on making mesoscale imaging capabilities more available to a broader class of materials needs to be at the forefront of future planning.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- HyMARC: Wide-ranging and fruitful collaborations have been established with other national laboratories and DOE Building Energy Sciences (BES) user facilities, universities in the United States and overseas, and seedling projects. These collaborations and interactions have greatly benefited the consortium and will undoubtedly be important in advancing this effort. Effective collaboration with HySCORE researchers is evident, and complementary research and development (R&D) activities are under way. A critical issue going forward is how to effectively manage and coordinate the multiple and diverse projects that will comprise the new HyMARC/HySCORE/seedling/new project enterprise. This is not an easy task. It will require an innovative management approach.
  HySCORE: The HySCORE core team has established extensive and valuable collaborations with other national laboratories and universities and research institutions in the United States and worldwide. These collaborations directly complement those in the current HyMARC activity, and they provide the foundation for an impressive and comprehensive capability in the consolidated consortium. The activities of the core team and project partners and collaborators are well coordinated and managed. The core team efforts are strongly leveraged by those collaborations, and they are greatly enhancing the progress being achieved in the overall project.
- The collaboration for this consortium and its sub-project is extensive and seems to be well coordinated. All key areas for the project's objectives are covered. The seedling projects enhance collaboration by providing a low-energy step to generate new tasks, collaborations, or approaches. It is also valuable to DOE's goals to have the vigorous collaborations with external research groups such as BES, University of Michigan, and non-U.S. organizations.
- One of the activities for the HyMARC team involves supporting the seedling projects. The mechanisms (i.e., meetings, workshops, etc.) by which seedlings interface with the HyMARC team members should be better articulated in the review documents and clearly spelled out for the seedling investigators.
- A broad set of partners was identified through seedling projects. The rest of the interactions with the broader community seem limited. Some of the relationships are only in discussion stages, such as hydrogen sponges with the University of California, Berkeley, so the list includes some members who are in the early, exploratory phase.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan (MYRDD).

- HyMARC: HyMARC is the centerpiece of the current DOE hydrogen storage R&D effort. The reviewer acknowledges and thanks DOE for initiating and sustaining a broad-based consortium of this kind that focuses on a foundational understanding and on tools/capabilities for modeling and characterization. It has become increasingly apparent that a deeper understanding of fundamental processes operative during hydrogen sorption reactions in complex hydrides is needed to facilitate discovery of storage materials that meet the challenging DOE targets. This project provides a direct and focused approach to developing improved materials in a systematic, controlled, and rational way. The current project focuses keenly on critical storage problems and issues. The new expanded consortium (HyMARC–HySCORE) will provide even more powerful capabilities and potential synergies, but it may be encumbered by the attendant management difficulties that invariably accompany a large endeavor of its kind. Successfully addressing that problem will pose a significant challenge for both the DOE and HyMARC management teams.
  HySCORE: The project directly supports the goals of the Hydrogen and Fuel Cells Program. The new expanded activity (merger of HySCORE, HyMARC, and associated seedling projects) will provide DOE with a truly world-class R&D capability that will be able to effectively address the challenging search for a hydrogen storage material capable of meeting DOE system goals in a rational and effective way.
- The HyMARC team is undertaking a major part of DOE's hydrogen storage research activities. The team members are additionally interfacing with international partners. The impact and visibility, nationally and

internationally, of HyMARC are impressive. At the point where such material(s) are developed, cost-effective, and producible, the challenges that 700 bar tanks pose to vehicle design and delivery infrastructure will fade away, and the growth curves in hydrogen vehicle markets will steepen.

- Each sub-project within HyMARC is playing a role to increase the likelihood of timely development of breakthrough materials that can have a major impact on hydrogen storage for transportation.
- As a whole, some important milestones have been achieved. Some important publications made a strong case for the team and the seedling interactions.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- HyMARC: The future work follows directly from prior progress and results. Extending the knowledge gained on model media to more complex systems will be an important, if not vital, aspect of the future work. This will include the role of surface oxides, additives/catalysts, and phase formation—especially in metal borohydrides—and reaction kinetics and mechanisms in encapsulated systems. The addition of hydrogen carrier R&D (H2@Scale activity) to the expanded HyMARC–HySCORE consortium is important, but it will divert resources from a core team that is already heavily committed. Moreover, that effort may require expertise that is currently missing from the core team. Discussions with the Chemical Hydrogen Center of Excellence (COE) team are strongly recommended to develop a clear pathway to meeting hydrogen carrier goals.
  HySCORE: The future work will clearly evolve as discussions between the current HyMARC and HySCORE teams proceed. It will be crucial to avoid simply merging the existing efforts within the two consortia without careful consideration of overlapping or duplicative efforts, "stovepiping" issues, and the possible elimination of sub-projects that have limited potential going forward. Candid discussions are needed. This is undoubtedly recognized by the management of the core teams, as well as DOE, but it cannot be emphasized strongly enough. As stated in the HyMARC review, this consolidation provides a comprehensive, wide-ranging, and most impressive array of capabilities and resources for DOE. However, a careful and creative approach to managing the new activity and establishing the proper framework for effectively conducting the multitude of R&D sub-activities is needed. This is a major challenge that requires input from the entire team.
- Initiating the data management plan is important to ensure the availability of important experimental and theoretical data to researchers and developers.
- The planned future work is a logical extension from the already ambitious goals of prior HyMARC and HySCORE activities.
- The proposed future work listed in the slide is somewhat uninspiring. It does not connect the accomplishments and challenges well and propose a vision to take the activities to the next level of maturity and technical complexity. A better focus on technical challenges and building strong, cross-cutting teams for the Phase 2 proposal with some key forward-looking milestones will make HyMARC a truly unique program in the DOE complex.

Project strengths:

- HyMARC: This is a comprehensive and well-coordinated R&D effort that is successfully providing in-depth understanding of the thermodynamics and kinetics of hydrogen sorption reactions that is facilitating the development of candidate storage materials. The consortium is also providing extensive theory support and experimental resources to assist seedling R&D projects. Solid progress was made in theory, synthesis, and characterization tasks in 2017–2018. Extensive and beneficial collaborations with other national laboratories and universities are in place. The work has set the stage for an expanded, and even more comprehensive, consortium in 2018. A strong and very capable R&D team has been assembled to conduct the work on this project. With only a minor exception (lack of in-depth chemistry expertise—especially for hydrogen carrier R&D), the team has experience and background in the areas relevant to achieving the project goals and objectives.

HySCORE: There is a very strong and capable R&D team in place. The characterization and diagnostic efforts provide a unique and powerful capability. The work on MOFs is important, and assuming further progress, it offers an opportunity for sorbent materials to make a serious and positive contribution.

- The consortium has developed, and hopefully will continue to develop, valuable diagnostic tools and analytical techniques necessary to develop hydrogen storage materials critical for the use of hydrogen as a transportation fuel. The seedling projects are a great way to appropriately initiate new activities and/or collaborations and effectively enable new physical and intellectual resources for hydrogen storage objectives. The ability to model materials and interactions over a continuum of relevant length scales is a very significant accomplishment. It is important to understand the discontinuities from different methods as models transition between scale ranges.
- The project has made a visible impact on hydrogen storage. Numerous publications have resulted from the work. This project represents the overview and management of several research projects. As such, the management team's strengths are also evaluated here. The leadership from Mark Allendorf and Tom Gennett represents two national laboratories with experience in leading a HyMARC or HySCORE team. The leaders have clearly defined objectives, and the projects have major scientific outputs.
- Overall, both teams' efforts were a strong strength. The model development made strong progress. The advanced characterization capabilities and methods made new capabilities available to the team. The surface chemistry instrumentation part was not adequately discussed, but the directions seem promising. The new synthetic methods component had some interesting results that need further exploration for realizing their potential. Overall, this is a strong team of experts making progress in multiple areas.

Project weaknesses:

- The consortium has developed, and hopefully will continue to develop, valuable diagnostic tools and analytical techniques necessary to develop hydrogen storage materials critical to the use of hydrogen as a transportation fuel. The seedling projects are a great way to appropriately initiate new activities and/or collaborations and effectively enable new physical and intellectual resources for hydrogen storage objectives. The ability to model materials and interactions over a continuum of relevant length scales is a very significant accomplishment. It is important to understand the discontinuities from different methods as models transition between scale ranges.
- HyMARC: The question as to whether detailed knowledge and understanding gained from "simple" model systems can be extended straightforwardly to more complex materials remains largely unanswered. The team must avoid diverting resources to understanding problems in systems that may not necessarily be relevant to those encountered in more promising materials. This is a difficult and enigmatic issue that has existed since the inception of the consortium. Of course, it is important to validate the models using well-understood systems, but a thoughtful and creative approach is needed to rapidly extend the work to the most appropriate and relevant candidate systems. It seems that the resources and core personnel are spread thin over a wide range and diverse set of research problems. This was especially apparent in 2017 with the infusion of a large number of seedling projects requiring large amounts of time and operational support from the core team. This problem will be compounded by the addition of the HySCORE team to the consortium. Time and resources must be allocated carefully.

  HySCORE: Although good progress has been made on understanding hydrogen sorption reactions in the C_2N and Ca oxalate systems, the fact remains that these materials have limited potential (at best) to meet the storage goals. Likewise, it is not entirely clear whether they serve effectively as model systems. It is therefore questionable whether continued work is justified.
- This project represents the overview and management of several research projects. As such, the weaknesses of the management team are also evaluated here. Each leadership group has clearly defined objectives. However, these objectives are not yet seamlessly integrated from the prior HyMARC and HySCORE ones. There does not seem to be a clearly articulated methodology for interacting with the seedling projects. Although the interactions are indeed occurring, there does not appear to be a systematic way for the seedling projects to feed in to the HyMARC team, and vice versa. This should be established and clearly articulated across all parties, if it has not been already.
- A few areas of concern are common for a project of this size. These comments are primarily about the overall organization of domains and management. Obviously, the project has a complex task of managing

and chaperoning resources for a multi-institutional, multi-disciplinary team. The individual performers and groups are, in general, working well. The team may consider streamlining project management. For example, a strategy for seedling integration into the activities and identifying people with more availability of time or technical background may benefit the overall progress. The resource planning and execution calendars should be maintained. It is unclear whether this is already the case, because it was not highlighted in the presentations. It is not clear if the teams share their individual plans and adjust the different moving parts adequately. Issues with access to the beamlines and contingency plans for achieving the objectives if resources cannot be secured is one example where more effort could be appropriated for reducing the project's execution challenges and risks.

Recommendations for additions/deletions to project scope:

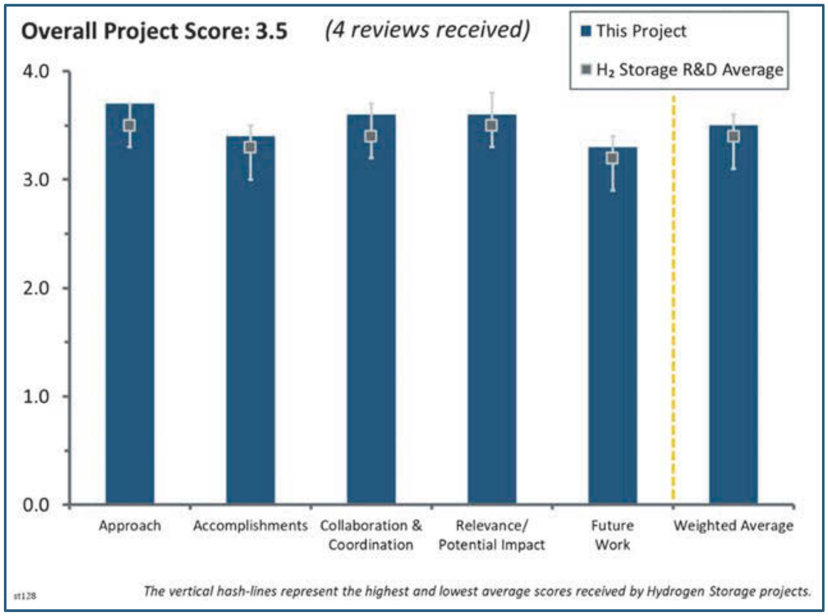
- HyMARC: Integration and coordination of complementary research efforts in the expanded HyMARC consortium will be a serious and challenging issue going forward. It will obviously require detailed planning by the management and DOE teams. "Stovepiping" and unneeded duplication of research efforts will undermine the positive aspects of a HyMARC–HySCORE merger. Although this problem is undoubtedly recognized by the HyMARC and HySCORE management team, a creative and dedicated approach to management of the expanded project will be needed to ensure success. Work on hydrogen carriers (part of the H2@Scale effort) is proposed for inclusion into the consolidated consortium. This places additional challenges on time and resources for the core team. It will be important to add additional chemistry expertise to the team (discussions with Chemical Hydrogen COE personnel are recommended for guidance and possible assistance).
  HySCORE:
    - *C_2N and Ca-oxalate*: Careful consideration concerning the efficacy and potential of the C_2N and Ca-oxalate work is needed. This should be done as part of the planning of the consolidated HyMARC effort.
    - *Hydrogen storage in MOFs*: Recent system analysis projections provided by the Argonne National Laboratory team (project ST-001) suggests that even with four hydrogen molecules per metal cation, the overall capacity in MOFs is still approximately two times lower than the DOE target. In view of this result, the HySCORE project team should conduct a candid assessment of its future work on MOF systems.

  Additional Comments for DOE and HyMARC/HySCORE management): Prior to the start of the HyMARC Phase 2 consolidated activity effort, it might make sense to convene a "Hydrogen Summit" with attendees from the consolidated HyMARC core team, DOE Hydrogen and Fuel Cells Program managers, and possibly some external experts to conduct a candid, frank, but informal assessment of the project's status and where it is headed. Some topics might include a discussion of impactful insights that have emerged in the last three years, what storage material candidates (if any) have risen to the top, which ones should be taken off the list, what dominant "foundational understanding" issues remain outstanding, what else DOE needs to know or do to move the bar, and what new resources and/or expertise are needed. That discussion and assessment might help the HyMARC management get on "the same page" in planning and implementing the Phase 2 effort.
- The project made progress. The overall recommendation is for a stronger and more streamlined management structure. This is crucial for improving the transparency of resource availability, planning, and progress by different members of the team. In general, phone calls and many such means are not adequate. Often, areas of concerns are not identified through such means. A serious attempt at handling the complexity of a large team, allocation of calendars, and tracking of progress needs to be modernized and made more seamless to improve productivity. This can help all team members have an aggregated view of the different activities and provide more opportunities for innovation and cross-cutting work across the board.

Project #ST-128: Hydrogen Materials—Advanced Research Consortium (HyMARC): Sandia National Laboratories Technical Activities

Mark Allendorf; Sandia National Laboratories

Brief Summary of Project:



This project addresses a lack of knowledge about hydrogen physisorption and chemisorption. Researchers will develop foundational understanding of phenomena governing the thermodynamics and kinetics of hydrogen release and uptake in all classes of hydrogen storage materials. Sandia National Laboratories (SNL) will (1) provide data required to develop and validate thermodynamic models of sorbents and metal hydrides, (2) identify the structure, composition, and reactivity of gas–surface and solid–solid hydride surfaces contributing to rate-limiting desorption and uptake, (3) synthesize metal hydrides and sorbents in a variety of formats and develop in situ techniques for their characterization, and (4) apply multiscale codes to discover new materials and new mechanisms of storing hydrogen.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- A systematic approach has been adopted to explore the energetics/thermodynamics, kinetics, and reversibility/cycling in sorbents and metal hydrides. The approach comprises theory/modeling, synthesis and processing, and detailed characterization methods to elucidate reaction mechanisms and probe the salient features of hydrogen sorption reactions in those materials. Collaborations with other Hydrogen Materials—Advanced Research Consortium (HyMARC) core team members and partners have contributed notably to the progress achieved in this reporting period. Overall, the approach is rational and is leading to progress that is having an impact on project goals and objectives.
- The research topics are well organized into a classification scheme, with the researchers responsible for each topic clearly listed and identified. This appears on slide 3, “Relevance and Impact.” The research strategies are clearly identified. The work is done in the area of sorbents (e.g., gate-opening metal–organic frameworks [MOFs]), borohydrides, and phase equilibria modeling.
- The approach is very well defined around energetics, kinetics, and reversibility. For energetic considerations, it is crucial that the nanostructuring/destabilization and tuning of enthalpy and entropic contributions be balanced against the challenges to reversibility. The kinetic considerations are identified, and challenges with optimizing all three of these areas are within the team’s capabilities.
- The project has a very good and comprehensive approach to understanding fundamental aspects of hydrogen storage materials. Most critical aspects are identified. In the examples, the project team could, and probably should, try to understand the materials with low melting temperatures that are currently the most promising.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project team achieved solid accomplishments and progress in numerous important areas. The most notable results include establishing a validated phase diagram for $Mg(BH_4)_2$, which is providing a framework for understanding materials properties and transport processes; developing a new understanding of the role of surface oxide layers in the dehydrogenation of $NaAlH_4$; providing a deeper understanding of the rate-limiting step(s) for MgB_2 (bulk) dehydrogenation; developing an improved understanding of nucleation and growth events and evolution in Mg-B-H materials using sophisticated scanning transmission x-ray microscopy (STXM) diagnostics; and identifying a new high-pressure method for infiltrating $Mg(BH_4)_2$ into a nanostructured host, which is important for probing kinetics and thermodynamics changes that may accrue by incorporating the metal hydride in a nanostructured template. (Data on hydrogen sorption behavior in the latter area are apparently not available at this time—those results will be important for guiding future experiments.) Progress in all of these areas is noteworthy and is providing a firm basis for future work.
- The work the team has done on sorbent materials indicates nickel nanoparticles form from aggregation of nickel atoms from the metal sites in MOFs after 700 bar or post-1000 cycles. The high-pressure work shows melting of $Mg(BH_4)_2$ occurs at 355°C (at 1000 bar H_2). Amorphization, occurring first, is considered a strategy to thermodynamically tune the material. The Mg-B-H phase diagram has been validated (along with Wood, ST-129).
- The progress made toward technical goals and DOE targets is satisfactory. The accomplishments presented provided some very interesting insights. For example, the role of Ti in the dehydrogenation of $NaAlH_4$ was revisited. The Delmelle et al. paper from 2014 was interesting, and the work by the current team provided better supporting evidence on the role of oxide phases of Ti with a strong link to the mobility of oxide ions as known for other supported catalytic systems.
- The project team has achieved outstanding accomplishments, both experimentally and computationally. This project is a great step forward.

Question 3: Collaboration and coordination

This project was rated **3.6** for its collaboration and coordination with other institutions.

- Extensive collaborations are evident. The fruitful collaborations with numerous investigators in the HySCORE program are especially noteworthy because they are providing a straightforward way to facilitate joint work that will be conducted in the consolidated HyMARC–HySCORE consortium. In addition, numerous collaborations with investigators at other national laboratories, universities, and research institutions are augmenting the work by the core SNL team. The project also supports several seedling projects, providing a mutually beneficial way to explore new topics and project areas. The critical challenge in the future will be to find the best ways to manage, organize, and coordinate the collaborative efforts among multiple institutions and projects within the much larger consolidated consortium.
- The SNL technical team has collaborative research with other HyMARC teams, including in computational modeling (with ST-129) and seedling projects.
- The project team has initiated extremely good internal (within HyMARC) and external collaborations.
- The collaboration is reasonable, exchanging samples with seedling projects at Argonne National Laboratory, University of Missouri–St. Louis, Liox Power/HRL Labs, National Renewable Energy Laboratory, etc. The team can benefit from more university connections to leverage the enthusiasm of graduate students and bring them into the community for training the future workforce in this domain.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The technical effort at SNL is an integral element of the overall HyMARC project and, as such, directly supports the goals and objectives of the Hydrogen and Fuel Cells Program (the Program). The principal investigator and the SNL team are conducting a research and development (R&D) activity that is closely aligned with the mission of the consortium and the DOE goals for the overall Program.
- The impact of the work is well documented. The characterization methods developed and results discussed have clarified some key issues. Overall, the work presented made strong progress in integrating capabilities and demonstrating results that are important for exploration of materials that have been known for a while. This is important proof that the new methods are better capable of providing detailed understanding or bringing the community closer to the ground truth. If there is any chance to increase either volumetric or gravimetric storage capacities of existing systems, it would be by using hydrogen storage materials such as this.
- So far, nobody understands why there is a gap of high-capacity hydrides with ambient working temperatures. Unfortunately, many important aspects in the reaction mechanisms of such materials are not understood. This project hints in the right direction. By advancing the understanding of these materials, this project lays the basis for the design and discovery of these sought-after materials with the right properties.
- The objectives are clearly laid out and are in line with objectives of the HyMARC program.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The future work is ambitious and intends to employ machine learning to define structure–property relationships. In addition to theory work, experimental work that examines amorphization as a strategy for improving storage properties will be undertaken. The team also plans to make contributions to in situ measurements.
- There is an urgent need for the characterization and better understanding of materials based on complex hydrides with low melting temperatures that alone show high reversible hydrogen uptake and release rates at low temperatures.
- The proposed future efforts are a straightforward extension of the prior work. The future work should provide a reasonable framework to develop an improved understanding of sorption kinetics and mechanisms, especially in metal borohydrides. However, it is surprising that the remaining challenges and future work (slide 20) contains no mention of the role of oxide layers in the reactions and transport of hydrogen in metal borohydrides. Specifically, it is unclear whether the $NaAlH_4$-oxide results can be extended to other complex metal hydrides (especially $Mg(BH_4)_2$). Additionally, it is unclear what the optimum oxide thickness is and what impact the oxide has on reversibility, etc. The "oxide issue" is clearly a serious one because it affects the performance (either positive or negative) in hydrogen sorption reactions in virtually every metal hydride under conventional operating conditions. Also, the motivation for achieving "pure nanoparticles of MgB_2 and $Mg(BH_4)_2$" is not readily obvious, especially in view of the agglomeration/clustering problem that often accompanies sorption cycling. Likewise, an understanding of the size distribution of metal borohydride particles in an encapsulated state is important (also, whether the particles reside in an amorphous, crystalline, or sub-crystalline state). Finally, it would be good to know the capacity "overhead" imposed by the nanostructured hosts that are being planned for use for future studies. All of these issues are important, but they are not addressed adequately in the future work statement.
- The work identified is reasonable. The modeling, synthesis, and characterization work proposed continues the overall approach. The encapsulation approach proposed for synthesis will need more creativity in improving the uniformity of performance for large-volume storage. Therefore, adequate emphasis on such promising areas needs to be coupled to the other parts of the work. There are some minor areas of concern. The team needs to identify the value chain better by dividing the future work among priority areas and leave some for the collaborators and other academic research groups for handling research on things

that might be considered low-impact activities. For example, the characterization team still plans to explore thermal degradation of MOFs using X-ray and neutron diffraction. This seems to be a good candidate that can be handled by the larger MOF community and may not provide the return on investment for the hydrogen storage community until there are very good candidates that can meet DOE targets. Owing to the diversity of MOFs, this seems like opening a large area of research without a good sense of targets and solutions needed to make them more thermally stable.

Project strengths:

- A very strong and capable core R&D team, including external collaborators, has been assembled to conduct this project. The project addresses a large number of critical issues that affect the eventual discovery and development of storage materials that meet DOE targets. The project comprises theory/modeling, synthesis, and advanced characterization efforts within a highly collaborative framework. The project is well coordinated and managed. The expansion of the project to include the HySCORE team, plus seedling activities and associated collaborators, will provide a powerful capability, but the management and coordination challenges will be daunting.
- The project is making true progress in the quest for hydrogen storage materials that hold promise for high capacity and reversibility. Fundamental research (e.g., amorphization) is being tied to material performance (e.g., utilizing amorphous phases to tune materials thermodynamically). This is the sort of connection that is necessary to have breakthroughs in hydrides and sorbent materials.
- The strength of the approach and the team is quite evident. Some important results and publications came out of the work. The progress is satisfactory, and capabilities are getting well integrated into the workflow. The partnerships and leveraging activities are moderate.
- This project has a very comprehensive approach and, so far, impressive results.

Project weaknesses:

- The weaknesses are minor. The project needs to develop a list of priorities and provide a strong technical rationale for ranking of such priorities. It is often hard to identify the strategic vision behind a large set of activities handled under the project. Therefore, a stronger vision and targets need to be identified in Phase 2. Another area of importance is shifting the focus from identifying the challenge of making nanocrystalline materials to developing a stronger plan for predicting, testing, and observing their behavior during cycling. The team needs to focus effort on classifying mechanisms and predicting materials behavior. This will save costs and research expenditures. Additionally, the research team needs to include a pipeline for materials that are more likely to achieve targets into the thought process. It is not clear if part of the time is spent with partners and collaborators to identify new and promising systems. Overall, the team is fully capable of improving the prioritization and allocation of resource problems identified above. Therefore, some are identified to improve focus and efficiency in an otherwise very exciting set of projects and progress reported. Additionally, when pursuing amorphization as a strategy in materials that must be thermally cycled for performance, the team should give careful thought to the recrystallization of amorphous structures during service.
- The results on the involvement of the oxide layer on reaction kinetics in $NaAlH_4$ are certainly intriguing; however, a clear pathway to understanding the relevance or translation of those results to other metal hydrides (especially metal borohydrides) is not evident. To this reviewer's knowledge, the fact remains that no experiments have been performed using pristine, oxide-free surfaces to establish a definitive baseline. There are challenges in conducting such experiments (ultra-high vacuum, in situ oxide removal/surface cleaning, detailed characterization during hydrogen exposure, etc.), but without that information, it is difficult to fully assess and understand the impact of the oxide on the reaction processes.
- The project team must give careful thought to whether amorphization plays a major role in thermodynamics (i.e., entropic terms), as the HyMARC team asserts, or whether amorphization more so affects kinetics (i.e., faster diffusion because of more grain boundaries and low electron density regions in the lattice).
- There is no focus on multinary composite systems with high capacities, low working temperatures, or high complexity.

Recommendations for additions/deletions to project scope:

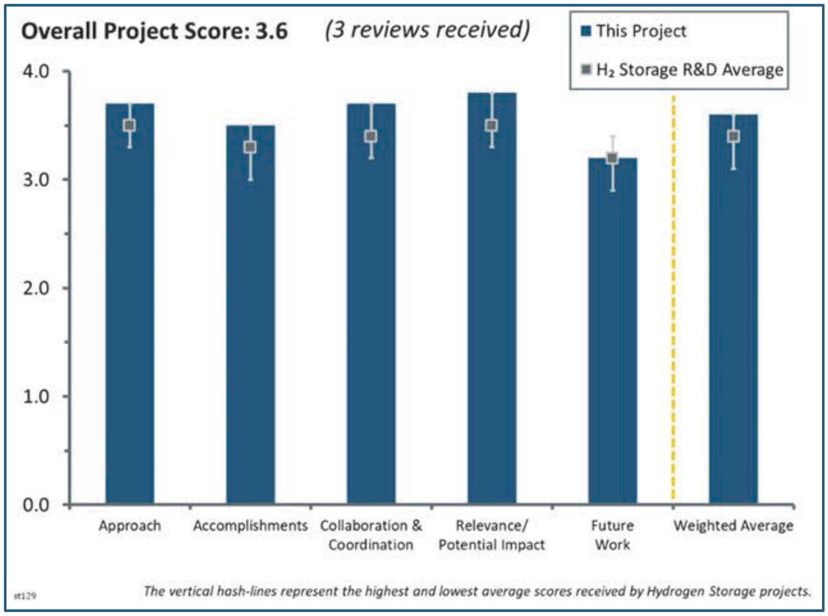
- Apart from addressing the issues raised in the "Future Work" and "Project Weaknesses" sections, by far the overarching issue for the HyMARC team will be how to coordinate and manage the consolidated consortium in a way that enhances inclusion and cooperation without duplication and "stovepiping" of efforts. Although this is a comment that is mainly relevant to the entire HyMARC effort, it nonetheless affects almost all aspects of the SNL work. This is an issue that the principal investigator and entire SNL team acknowledge and are actively engaged in solving, but the importance of focusing clearly and "getting it right" should be reinforced.
- Some more effort on mesoscale imaging and connections to mesoscale modeling needs to be allocated. For reduced scope, it is not clear that MOF characterization work is the best use of resources.
- The group should take into account the more complex systems of multinary composite systems with high capacities, low working temperatures, and high complexity.

Project #ST-129: Hydrogen Materials—Advanced Research Consortium (HyMARC): Lawrence Livermore National Laboratory Technical Activities

Brandon Wood; Lawrence Livermore National Laboratory

Brief Summary of Project:

The Hydrogen Materials—Advanced Research Consortium (HyMARC) is providing community tools and foundational understanding of phenomena governing thermodynamics and kinetics to enable development of solid-phase hydrogen storage materials. HyMARC team member Lawrence Livermore National Laboratory (LLNL) is conducting porous carbon synthesis; X-ray absorption/emission spectroscopy (XAS/XES); and multiscale modeling including density functional theory (DFT), ab initio molecular dynamics, phase-field mesoscale kinetic modeling, and kinetic and quantum Monte Carlo (QMC).



Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach on this theory/modeling project addresses a wide range of critical phenomena and issues and obstacles that have an impact on our understanding of hydrogen sorption reactions in storage materials. Initial work on model systems is being extended to more promising (and complex) materials. As noted by the principal investigator, the focus is three-fold: (1) bridging scales via multiscale integration, (2) getting past model systems and moving to “real” materials, and (3) leveraging the interaction between experiments and theory. The approach is comprehensive, rational, and strongly coupled to the experimental work being conducted by the HyMARC core team and seedling project partners. This effort is a critical element of the entire HyMARC project. The project team is addressing important issues in an innovative and impressive way. Moreover, the team has been willing and able to make mid-course corrections to the approach and project focus as needed.
- The project’s focus on theory and modeling to remove barriers to these areas for the particular case of hydrogen storage systems is an excellent one to tackle. As such, progress is being made in understanding the modeling inaccuracies to thermodynamic terms such as entropy. The Mg-B-H phase diagram has been developed. These efforts are poised to have lasting impacts on gas/solid models (even those outside of the scope of hydrogen storage).
- The LLNL team’s approach is focused on the theory about handling the multiscale challenges involved in the hydrogen storage phenomena, coupled to validation activities. A multiscale scheme is proposed. The team may be well advised to realize that the traditional multiscale approach will meet a range of challenges in scale bridging. This review will not focus on the multiscale challenges when judging the approach. The main strength of the approach is in the atomic-scale modeling. The multiscaling part is somewhat unremarkable and will be hard to accomplish at the level of clarity provided by the atomic-scale results.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Solid progress has been made in numerous areas. The collaborations with seedling partners are especially noteworthy, and the results from those joint studies are leading to improved understanding of important phenomena and processes. Some especially notable accomplishments include:
  - Elucidating the decomposition mechanism of MgB_2; predicting the Mg-B-H phase diagram (a collaboration with Sandia National Laboratories [SNL] and Pacific Northwest Laboratory [PNNL] with a focus on a high-pressure regime).
  - Understanding and predicting changes in entropy due to surface anharmonicity from molecular rotations, and showing how a confining medium can “freeze” anharmonic rotations and destabilize the hydride.
  - Demonstrating that confinement stress dramatically affects thermodynamics and kinetics in nanoconfined metal hydrides.
  - Indicating that surface oxide facilitates the dehydrogenation of $NaAlH_4$—resulting in important implications for other complex hydrides.
  - Using simulated interactions of ethers and metal hydrides, showing that etherates destabilize the surface B and generate structural defects (collaboration with the University of Hawaii seedling project).
- The strong set of accomplishments presented demonstrate the excellent value the team is bringing to HyMARC. It is evident that multiscale schemes are always hard to match as a whole. The accomplishments are primarily atomic-scale in nature. The work on multiple systems demonstrates a strong capability in data-driven corrections of DFT enthalpy from previous computations and very good, plausible mechanistic explorations of MgB_2 and $NaAlH_4$ systems.
- The project is making excellent progress. The role of oxides at the surface of hydrides has been elucidated as important. New mechanisms such as B-B bond breaking for the step on adsorption of hydrogen in MgB_2-THF (etherates) have been put forth from theory and modeling leading to new (and effective) “design rules.” Further experimental validation of the B-B bond-breaking mechanism is necessary.

Question 3: Collaboration and coordination

This project was rated **3.7** for its collaboration and coordination with other institutions.

- Collaboration with seedling teams and with other HyMARC (and prior Hydrogen Storage Characterization Optimization Research Effort [HySCORE]) teams is visible and is a major strength in terms of validating this theory and computational work.
- Collaborative efforts are critical to the success of this project. The project team has done an excellent job of collaborating in an effective and timely way with experimentalists and other theorists within the HyMARC, HySCORE, and seedling projects. The collaborations have been valuable and are definitely leading to enhanced understanding and insight. The only concern is that the extensive collaborations could divert the time and resources of the project team and limit the ability to conduct work on the “core” problems of the consortium. That potential problem will be compounded as more sub-projects requiring theory/modeling resources are introduced into the consolidated HyMARC consortium.
- The team contributed by improving the overall intellectual quality of the discussions and results by providing strong predictive results on multiple systems. The phase field model from Michigan State University seems to be a good direction, but not much regarding the results was discussed. LLNL has an Arbitrary Lagrangian–Eulerian 3D (ALE3D) for large-length-scale work. It might be worth discussing some work with the ALE3D team. Idaho National Laboratory’s Multiphysics Object Oriented Simulation Environment (MOOSE) framework has a very good phase-field module. It might be worth exploring such connections. Symmetry-adapted perturbation theory (SAPT) potential work is very useful and can potentially help with many other systems if it can be standardized and tested for thermodynamic accuracy.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is pushing forward on the boundaries of some computational areas that have not been worked out. For example, the anharmonic contribution to entropy improves model fits to experimental data. These effects are able to explain the role of nanoconfinement and amorphization of the lattice on hydrogen desorption and uptake kinetics.
- This project is a critical component of the HyMARC effort and directly supports the HyMARC core mission of providing foundational understanding of important thermodynamic and kinetic phenomena and processes in hydrogen storage reactions. The project is closely aligned with HyMARC goals and objectives and, as such, is closely aligned with the goals and objectives of the Hydrogen and Fuel Cells Program.
- The impact is strong for the domains where theoretical work was performed. It is hard to quantify whether the multiscale scheme proposed is successful as a whole. Much work is needed if HyMARC decides to invest in codes that can explore mesoscale chemistry. The atomic-scale work has definitely made a significant impact and will continue to do so.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work is a direct and sensible extension of prior investigations. There are many intriguing topics that are especially important. A few examples requiring more detailed study include:
    - Developing an improved understanding of the role of surface oxide layers in dehydrogenation reactions in complex hydrides. Specifically, it is important to discover whether the results obtained on $NaAlH_4$ are extendable to other metal hydrides, especially metal borohydrides. Another question is about the optimum oxide thickness needed to facilitate dehydrogenation and whether a sub-monolayer oxide is effective.
    - Gaining a better fundamental understanding of how catalysts and additives alter the hydrogen sorption reaction kinetics in complex metal hydrides.
    - Developing a better understanding of the effects of B- and N- doping in C-containing materials (in collaboration with PNNL). The change in isosteric heat has been ascribed to a defect-mediated process, not chemical doping. If correct, the nature of the defect and whether this is a general phenomenon in carbon materials would be interesting questions to explore. The addition of projects from the HySCORE effort (i.e., core and seedling projects) will undoubtedly have an impact on future work on this project. A careful prioritization of project needs and impact must be made to ensure that the most important issues and problems are addressed in the most effective and timely way.
- The proposed future work is in line with prior findings and is a logical extension. In fact, the prior findings have led to opportunities to explore new ideas (such as a study of amorphous materials). As another positive impact, much of the future work will hinge on interfacing with seedling projects.
- The future work proposed on sorbents includes the completion of calculations on hydrogen physisorption and the stability of functionalized covalent organic frameworks (with a seedling from the National Renewable Energy Laboratory), as well as the establishment of a "best practice" for DFT calculations of hydrogen physisorption on MOF-74, in collaboration with the Lawrence Berkeley National Laboratory and SNL. This seems reasonable; the addition of anharmonic effects on the thermodynamics of metal hydrides is promising and can include MOFs. The publication of the anharmonic free energy database for model complex hydrides is important. However, pressure/temperature effects still need some work. It is hoped that the team will be able to dedicate resources to bring these capabilities forward through the streamlining of workflows. In the chemistry of metal hydrides, hydride intermediates within the high-temperature ab initio molecular dynamics (AIMD) of $NaAlH_4$ and $Mg(BH_4)_2$, with and without Ti, are very complex, and development of reactive molecular dynamics approaches is needed. It was not clear whether AIMD or tight-binding density functional theory (TB-DFT) dynamics can achieve the timescales, even after using

large-scale computing resources. The objective of identifying and validating pathways for closo-borane formations from MgB_2 is interesting. It is not clear why this is a capability that is preventing the materials community from succeeding in achieving their proposed goals. More details on the LLNL multiscale modeling framework for hydriding kinetics is definitely of interest. Finally, comparing the nucleation model with scanning transmission x-ray microscopy (STXM) microstructures is hugely important. The hydrogen storage community may find some work currently pursued by the battery research community (e.g., the study of charged/expensed battery material imaging has made a lot of progress in the past five years). The additive work will require a stronger connection to multiscaling and traditional materials modeling efforts of phenomena at the grain boundaries. This part of the team may need some reinforcements. In standards and tools, some work in Mg-B-H and pairwise potential was indicated. In DFT work, the use of materials genome machinery, databases available through the efforts of the National Institute of Standards and Technology, and many other free (but still requiring full-time equivalent resources) will be able to aggregate the future work into an organized framework. It is recommended that the team discuss the overall progress and gaps with the materials project team, as well, to encourage others in the community to contribute to screening hydrogen storage materials using DFT. In other words, there are many options for expanding activities and attracting/leveraging funding from other sources.

Project strengths:

- This is an impressive project being conducted by a highly qualified and experienced team. Extensive collaborations have augmented the overall impact of the project. It is a critical element of the overall HyMARC effort and is providing critical foundational understanding and guidance for experimental work.
- The atomic-scale work and DFT calculations, in particular, are the main strengths of the effort. The progress made in improving predictive capabilities and correcting long-help errors in both experiments and theory provide great proof for the impact the project had in the previous performance period.
- Overall, the project is excellent/outstanding. The theory and modeling work done is an essential cornerstone to other HyMARC and seedling endeavors.

Project weaknesses:

- The theory and modeling team should continue to make every effort to experimentally validate the findings. Particularly, the B-B bond breaking by etherates, as a mechanism for the uptake of hydrogen by MgB_2 adducted with tetrahydrofuran (THF), would be validated by relevant spectroscopic techniques. Those techniques appear to be available within the HyMARC group.
- This is not necessarily a weakness but a comment/observation: It is not entirely clear how specific topics were selected for detailed study in this project. It would be useful to understand how projects are prioritized and selected. The main reason for raising this issue is that there is some concern that the project could become a victim of its own success—i.e., time and resources of the project team could be stretched so thin by multiple needs that the impact in any specific area becomes diluted. This will be especially important as the consortium grows with the addition of HySCORE and associated seedlings.
- The weakness of this project is in other length scales compared to atomic scale. The areas of reactive dynamics need more work. The phase-field and grain-boundary phenomena are not at the forefront of this project. Some weaknesses do not necessarily need to be corrected just because a multiscale scheme was proposed. Therefore, the team is encouraged to evaluate the plan and continue the good work.

Recommendations for additions/deletions to project scope:

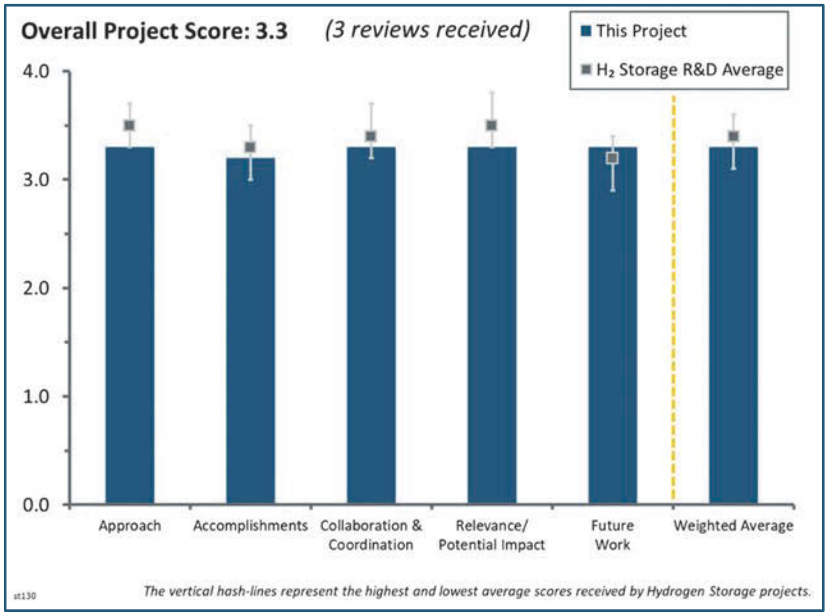
- It is recommended that the team evaluate progress of the multiscaling strategy and efforts. The addition of reactive dynamics in the mesoscale is recommended to match STXM and similar progress in experimental mesoscale domains. The effort with MgB_2 and other borohydrides seems less exciting compared to making progress with reactive dynamics at the grain level in mesoscale for helping with resolution of stress and reaction progress. For example, some of the contrasts in STXM imaging can be evaluated using DFT approaches developed for the scanning tunneling microscope (STM) in the past. Additional input from the phase-field models needs to be evaluated for the actual strength in predicting physically meaningful insights. Otherwise, much of the phase-field models suffers from unphysical assumptions regarding the

phase-field parameters and a lack of mechanics in their models. Therefore, an objective analysis of the multiscale strategy will help to consolidate the progress from more predictive techniques such as DFT at an appropriate level.
- There are no specific recommendations for changes to the project scope. Thoughtful and candid discussions with the entire HyMARC team need to occur so that the most critical needs are addressed and the proper focus is achieved in this project going forward.

Project #ST-130: Hydrogen Materials—Advanced Research Consortium (HyMARC): Lawrence Berkeley National Laboratory Technical Activities

Jeffrey Urban; Lawrence Berkeley National Laboratory

Brief Summary of Project:



The Hydrogen Materials—Advanced Research Consortium (HyMARC) is providing community tools and foundational understanding of phenomena governing thermodynamics and kinetics to enable development of solid-phase hydrogen storage materials. Lawrence Berkeley National Laboratory (LBNL) will (1) focus on light materials and synthesis strategies with fine control of nanoscale dimensions to meet weight and volume requirements, (2) design interfaces with chemical specificity for control of hydrogen storage/sorption and selective transport, (3) explore storage concepts, (4) develop in situ/in operando soft X-ray characterization capabilities in combination with first principles simulations to extract details of functional materials and interfaces, and (5) refine chemical synthesis strategies based on atomic-/molecular-scale insight from characterization/theory.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project team has implemented an approach comprising theory/modeling, synthesis, and characterization of metal hydrides, sorbents, and hybrid nanoscale systems. The project facilitates access by HyMARC investigators to the extensive capabilities of the Molecular Foundry and Advanced Light Source (ALS) at LBNL. The approach is evolving to address important problems and obstacles to hydrogen sorption and reversibility in more promising storage material candidates.
- The LBNL research team is focused on both computational and modeling work and experimental work, including facilitating interactions with the X-ray spectroscopy team at the ALS. Both areas (computational and experimental) are functioning collaboratively with other groups in the HyMARC team. Also, the group is interacting with the seedling projects, particularly seedling projects on graphene-wrapped borohydrides and etherate–MgB_2 rehydrogenation.
- The approach is fundamentally strong, with a good connection between theory and experiments. The novelty of the approach and accuracy of the experiments are well suited for the problem.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The progress made to date is impressive. The research on the fundamental side has elucidated the phase formation (alpha, beta, or gamma) in graphene-wrapped nano-$MgBH_4$. Other progress has been made in the important issue of examining surface and bulk spectroscopy in a single sample via total electron yield

(TEY) and total fluorescence yield (TFY), respectively. Finally, the successful design and demonstration of an in situ X-ray absorption spectroscopy (XAS) flow cell (1 bar and 400°C) is a major accomplishment.
- The project team achieved progress in several areas. The most notable were controlling the $Mg(BH_4)_2$ phases in a reduced graphene oxide (rGO) host; incorporating a highly active hydrogen dissociation catalyst to functionalized graphite nanoribbons; developing in situ XAS for hydrogen sorption measurements; and modeling high-pressure hydrogen storage in metal–organic frameworks (MOFs), with results validated by experiments. Overall, compared to prior reporting periods, the technical effort in 2017–2018 was more suitably focused on materials that at least have potential to be viable storage candidates. However, it is not entirely clear what criteria the principal investigator and his team have used to select specific topics for study. The team presented very little information concerning the potential of the different materials to meet DOE goals or to serve as model systems that might inspire work on more relevant materials. Some clarification and elaboration would be helpful. Likewise, the presenter should state the actual impact and/or importance of the accomplishments listed in the slides. An experimental result in a review of this kind is useful only if it is shown to be meaningful or to have relevant impact on the understanding of an important issue.
- The accomplishments listed are well coordinated. The team made some important advancements in graphene nanoribbon (GNR) materials. Extending this to other hybrid materials is quite promising. The team also performed theory work with a great degree of detail and innovation. It is unclear why Grand Canonical Monte Carlo (GCMC) and Quantum Monte Carlo (QMC) indicated for MOFs show only GCMC. It is also not clear why QMC was performed (multiple hydrogens in QMC calculations can be interesting, as can high oxidation state metal centers) and what the finding was.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- Collaborations are in place with investigators in the HyMARC and Hydrogen Storage Characterization and Optimization Research Effort (HySCORE) core teams and seedling projects. It is anticipated that collaborations will expand as the technical efforts in the new consolidated consortium are coordinated and come up to speed.
- As mentioned before, the LBNL team is collaborating with both other HyMARC teams and seedlings.
- Interactions with collaborators is somewhat minimal. The team can expand connections and increase the impact of both theory and experimental capabilities developed.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project generally aligns with the goals and objectives of the Hydrogen and Fuel Cells Program. A significant aspect is that the project facilitates access to advanced diagnostic and synthetic capabilities at the LBNL ALS and Molecular Foundry. These capabilities are critically important for the overall HyMARC activity and will be of great benefit to the consolidated HyMARC–HySCORE consortium and associated seedling projects.
- The contributions of this team are important. They are responsible for the beamline programs and gaining access to beamlines at DOE laboratories and international facilities (when needed). This is a clear and unique contribution made by the team (in addition to the above-noted collaborative accomplishments).
- The project team made some major advances in this time period. The effort is headed in a strong technical domain with the addition of increasingly relevant systems. Thanks to strong mechanistic understanding, the team has the capability and sufficient experience to expand the effort and provide simpler diagnostic tools for scaled volumes of samples in conditions closer to the realistic storage environment. In particular, higher-pressure environments will need further maturation of the current XAS techniques. The target of extending to 1 bar may not achieve the proposed objective.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work follows from major accomplishments (including developing a high-pressure, 10 bar gas cell that operates at 600°C).
- The future work scope is quite large and includes some of the harder milestones. The team is capable of handling this but needs to clearly articulate a prioritization of possible areas listed.
- The future work extends the work conducted in 2017 and 2018. The future work plan is rational and consistent with the overall HyMARC goals. One question concerning the systematic MOF study (last bullet) is that it seems that several other studies have been done on the relation between structure and hydrogen adsorption in MOFs. It is unclear in what way the present study differs from the prior work and what new information is expected. Also, as stated later in this review, careful consideration of the capacity "overhead" imposed by encapsulation matrices should be considered and reported.

Project strengths:

- The project is well balanced and developed a well-integrated approach for synthesis, characterization, and theory/modeling of the selected systems. The reversibility of $Mg(BH_4)_2$/rGO was explored. The challenges are not surprising, but the approach is well grounded in good experimental approach. In situ XAS measurements at 1 bar of hydrogen detected MgH_2. The fundamental insights are important outcomes.
- A capable project team with extensive experience in materials synthesis, advanced characterization, and modeling has been assembled. The project provides direct access to unique characterization tools that are of great benefit to the overall HyMARC effort.
- The project has numerous publications and presentations. The research is making large contributions to the HyMARC team through discoveries (at LBNL) and in collaboration with HyMARC team members at other laboratories, as well as the seedling projects.

Project weaknesses:

- The overall weakness is lack of a systematic management of complexity and scale to address realistic pressure–temperature conditions under which hydrogen storage materials and systems will operate. The in situ work is promising, but the challenge will always be the high-pressure and high-temperature cells. The theory effort is relatively modest. A stronger integration of theory in the design of experiments is recommended. The remaining challenges are identified, but the future work is clearly aligned as a response to challenges. The strategic intent in the planning of future work needs to follow the objectives, and organization of theory efforts around some of the more intractable problems are needed; examples include more reliable screening of MOFs beyond GCMC, exploring innovative approaches to materials in rGO reversibility, and better control over synthesis and scale-up problems. As stated in the objective, the connection between theory and synthesis is important. This connection needs to be more direct. Also, the sharing of codes and data seems to have taken a back seat. Better management of ancillary tasks that are important for the community requires a stronger project management framework and assignment of efforts.
- It was very difficult to ascertain either from the slides or from the presentation what the real impact is of each accomplishment. For example, it is unclear why "pure phase control" in slide 8 is important. In slide 9, "Reversibility in…" could easily be re-stated as "Poor Reversibility in…" This is hardly a stellar example of reversibility. Also, in slides 11 through 15, it is not clear what important information is conveyed by the results of in situ and ex situ characterization. Likewise, in some of the "Accomplishment" slides (e.g., slides 8 and 14), the phrase "First example of …" or "First achievement of …" is used. A first demonstration of something may be important, but a statement about why it is important is far more useful. The project team is urged to clarify and augment future presentations with statements about the importance and impact of the results. An important addition to future presentations should be a statement of what volumetric and gravimetric capacities are expected from the new materials, assuming complete success. For example, in the $Mg(BH_4)_2$ nanoparticles wrapped by rGO, the gravimetric penalty imposed by the rGO host is unclear. Likewise, the overhead imposed by GNRphenIRCp*OH2 is unclear. If it is onerous, then it is time to rethink the encapsulation approach.

- There was no data management plan found in the materials submitted. There were two new patents mentioned, but there was no indication as to what the patent was for or what the patent number was (so that it could be easily looked up). Presumably, the in situ gas cells were patent opportunities; however, after reading the slides and listening to the presentations, it remains unclear whether this is the case.

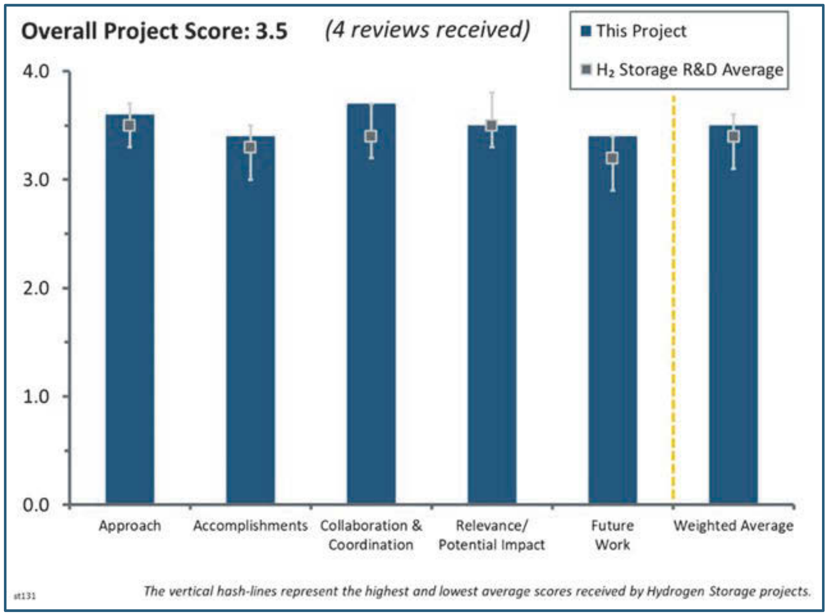
Recommendations for additions/deletions to project scope:

- The team should give additional thought to experiments that probe the role of surface oxides on hydrogen sorption behavior in complex hydrides. Based on recent results from the HyMARC team, the oxide could be a blessing or a curse, depending upon the system being studied. This is clearly an important topic and is one that the LBNL team seems qualified to address in collaboration with other HyMARC investigators.
- The team should develop better mapping between challenges and future work proposed. The project has very well-defined objectives; however, not all these connections are explored with equal emphasis. The project team may need to carry out some rescoping to establish greater cross-cutting.

Project #ST-131: Hydrogen Materials—Advanced Research Consortium (HyMARC): National Renewable Energy Laboratory Technical Activities

Thomas Gennett; National Renewable Energy Laboratory

Brief Summary of Project:



This project represents a collaboration between national laboratories to investigate the properties of promising new hydrogen storage materials, and works in coordination with the Hydrogen Materials—Advanced Research Consortium (HyMARC) core team. The National Renewable Energy Laboratory (NREL) leads the collaboration, which includes Lawrence Berkeley National Laboratory, Pacific Northwest National Laboratory, and the National Institute of Standards and Technology. The objectives are to (1) develop new characterization capabilities such as nuclear magnetic resonance (NMR) spectroscopy, diffuse reflectance Fourier-transform infrared spectroscopy (DRIFTS), calorimetry, diffraction, and scattering, and (2) validate performance claims and theories critical to the design of new hydrogen storage materials.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach comprises two distinct elements: (1) development and enhancement of characterization/diagnostic capabilities and use of those methods for validation of hydrogen storage claims and concepts, and (2) rational design of selected hydrogen storage materials and advancing insight into thermodynamic and kinetic obstacles to achieving optimum storage performance. The first aspect builds on core capabilities, expertise, and experience at NREL and partner organizations. It provides the U.S. Department of Energy (DOE) with a unique set of capabilities; NREL has become DOE's "go to" organization for sample and concept validation and measurement protocol implementation. The second part of the approach is less compelling as a stand-alone NREL effort. In fact, it could easily be argued that the second aspect falls more naturally within the purview of the HyMARC activity. With the pending consolidation of the legacy HyMARC and Hydrogen Storage Characterization Optimization Research Effort (HySCORE) projects, that confusion will hopefully be resolved, and a candid assessment and evaluation of the NREL materials development effort will hopefully be a high-priority topic.
- The approach of the NREL team is to expand core capabilities and also to aid in materials development. One extremely valuable aspect of this effort is in the leading of round robin sample measurement in order to baseline measurement metrics for hydrogen storage. This effort should be extended to other areas for which variability of results in the literature makes the underlying materials phenomena intractable.
- This project has a very comprehensive approach. In particular, the analysis and results from the inter-laboratory comparison are very impressive and are a big step forward for the scientific community.
- This is well-organized work handling some of the major issues that have plagued the community during the hydrogen storage research done in the past decade.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Good progress was made on development and application of measurement and validation methods. Particularly noteworthy accomplishments include (1) completion of inter-laboratory comparisons of volumetric capacity and implementation of standard measurement protocols, (2) characterization of the importance of packing density (and measurement methods) on volumetric capacity, (3) development of advanced variable-temperature pressure-composition isotherm and thermal conductivity measurement apparatus and methods, and (4) extensive characterization and diagnostic support for several seedling projects. The materials work focused on characterizing the behavior of small pore materials (e.g., calcium [Ca] oxalate), two-dimensional C2N framework materials, and effects of boron (B) and nitrogen (N) doping on the isosteric heats of adsorption for hydrogen in carbon materials. Intriguing results were obtained in all areas. However, based upon the results obtained in prior years and the results reported in this review, it is not obvious that the Ca oxalate and C_2N work should be continued. In both cases, the future prospects for these materials as viable storage candidates are dim. Moreover, a compelling case has not been made concerning either a pathway to achieving higher performance or how these materials might serve as model systems that could inspire work in related materials. The N- and B-doping effects on heats of adsorption seem to be more complex than originally thought (i.e., a defect-mediated process rather than chemical doping may in fact be operative). Careful experiments that definitively test the defect mediation versus doping ideas and identify of the relevant defect type(s) need to be formulated.
- In addition to the round robin efforts and paper that disseminates findings of the round robin so that measurements are performed more consistently across many laboratories, other activities include (1) building a unique thermal conductivity apparatus, which will enable assessment of cracking and strain during hydride cycling, and (2) discovery of phonon effects for hydrogen uptake in sorbent materials.
- The development of new techniques to analyze the material properties are highly appreciated. The inter-laboratory comparison study, along with its analysis, is a big achievement of this project.
- The primary objectives were mostly accomplished. Support of HyMARC and seedling teams is commendable. This team is working well.

Question 3: Collaboration and coordination

This project was rated **3.8** for its collaboration and coordination with other institutions.

- Extensive collaborations between the NREL investigators with the HySCORE and HyMARC core teams, other national laboratories, universities, private companies, and seedling projects are extending and advancing the impact of the NREL project. The most beneficial collaborations are focused on measurement and validation, protocol formulation, and new technique development. The collaborations are well coordinated, and there is close cooperation among all partner organizations.
- The team is collaboratively interacting with other HyMARC groups. Collaboration with seedling projects is not apparent (if it is ongoing). Given the massive collaborative effort required for completion of a round robin, this comment is less of a criticism and more of an observation.
- Project collaboration with other institutions is enormous.
- No deficiencies were identified in this project. The team is working well with others.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The technical activities at NREL are an important component of the overall DOE Hydrogen and Fuel Cells Program portfolio of projects. NREL has become the DOE focal point for measurement and validation of hydrogen storage material properties, comparison, and verification of results obtained at other laboratories,

and development of definitive measurement protocols. The NREL materials work is a less critical adjunct to the characterization effort. The consolidation of the HySCORE and HyMARC activities should clarify and improve the nature of the NREL involvement in materials development, as well as efforts directed toward developing a foundational understanding of thermodynamics and kinetics in storage materials.
- This project is serving an important need. It is, in fact, helping HyMARC achieve some of its targets and goals.
- The project is aimed in the right direction. The final material to solve all problems has not been found yet. Nevertheless, methodologies and instruments developed in this project can be used to promote research on the most interesting materials.
- Unique and impactful areas are being pursued with the developments in this project.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- Work on kinetic control through manipulation of pores is of great importance, both for the direct storage of hydrogen and for the purification of hydrogen, and should be continued.
- The proposed future work follows directly from the results obtained in 2017 and 2018. At some point in the characterization/diagnostics effort (relatively near term), it seems that the focus will shift from technique development and formulation of measurement protocols to more routine application of the techniques to provide additional direct support for collaborating partners and seedling projects. Given the concerns about the viability of C_2N and Ca oxalate, either as candidate materials in their own right or as model systems for development of more suitable materials, the proposed future work on those materials is questionable. Thoughtful and candid discussions concerning future work, if any, on these systems should be a priority in the newly consolidated HyMARC project.
- The project's proposed future work builds upon past successes.
- The future plan has more emphasis on C_2N materials. It is not clear why any other core capability development or improvements in the efficiency of measurements or some of the outstanding challenges are not identified as future work.

Project strengths:

- The project is extremely meritorious. The leading of the round robin, as well as the development of unique capabilities (e.g., thermal conductivity apparatus) and fundamentally new ideas (e.g., phonon effects), results in meaningful contributions to the HyMARC group.
- The NREL team is very capable, with expertise and experience in all areas of the project. The characterization and diagnostic work is first-rate and is providing DOE with a vital resource for evaluating materials and storage processes.
- The project strength is in the service provided to different participants in making appropriate measurements and development of core capabilities. It has made a difference and has kept HyMARC from becoming a fundamental science effort.
- This is a very successful project. In particular, the outcome of the inter-laboratory comparison test and the conclusions drawn thereof are impressive.

Project weaknesses:

- The NREL materials development work, especially the C_2N and Ca oxalate efforts, are only marginally valuable. Without major advances, those materials are simply non-starters, serving neither as viable storage candidates themselves nor as model systems that might inspire work in related materials. A careful review of these projects should be performed within the consolidated HyMARC project, and a rational decision should be made concerning the path forward (if any) for these materials.
- The project plan and future scope seem to lack excitement and new ideas. The team can propose faster and more accurate measurements. The team identified better communication with theorists as a challenge but did not propose the future work to keep growing the activities to have an impact on the broader community.

- It would be desirable to gain a deeper understanding of the phenomena and even closer collaboration with simulation groups.

Recommendations for additions/deletions to project scope:

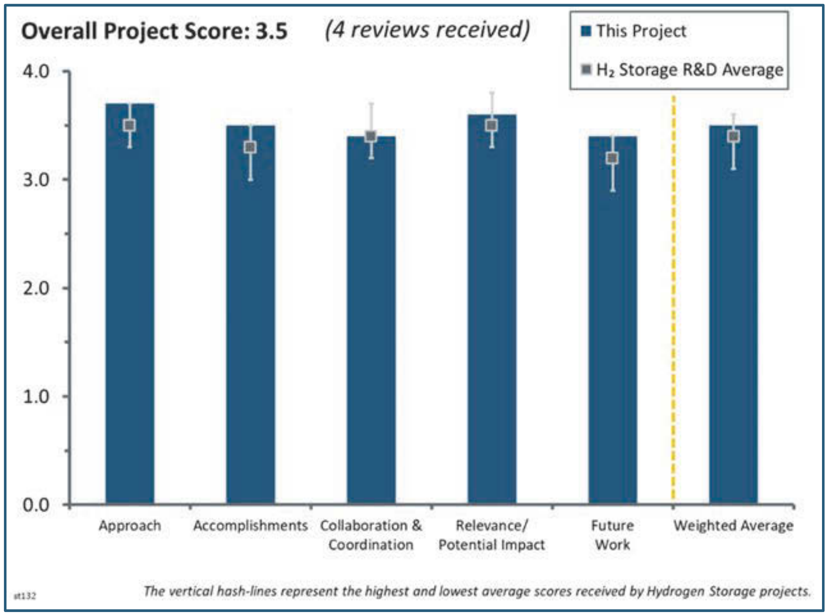
- Rethinking the scope with the identification of systems other than C_2N will be helpful. Many of the HyMARC team will need help with scale-up. Engagement of a broader community of researchers and creating a more open system for access and project data sharing can also be part of the work going forward.
- It is anticipated that the new HyMARC framework will provide NREL with a more natural home for more relevant materials work.
- Stronger collaboration with groups doing computer simulations, and especially molecular dynamics simulations, could be beneficial.

Project #ST-132: Hydrogen Materials—Advanced Research Consortium (HyMARC): Pacific Northwest National Laboratory Technical Activities

Tom Autrey; Pacific Northwest National Laboratory

Brief Summary of Project:

This project is part of a collaboration between national laboratories to develop new characterization capabilities to investigate the properties of promising new hydrogen storage materials. The project works in coordination with the Hydrogen Materials—Advanced Research Consortium (HyMARC) core team. Pacific Northwest National Laboratory (PNNL) will focus on nuclear magnetic resonance (NMR) spectroscopy and calorimetry to complement parallel efforts at other national laboratories. The project will also work toward validating claims and theories critical to the design of new hydrogen storage materials that show promise.



Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach comprises both experimental and theoretical elements. The principal focus is on predicting and characterizing reactions in boron-doped carbon and $Mg(BH_4)_2$ using in situ, variable-temperature NMR to identify intermediates and products, as well as variable-pressure reaction calorimetry to measure hydrogen sorption enthalpies. The approach also uses theory to predict intermediates, products, and binding energies. The two aspects of experimental and theoretical elements are closely coupled, and the approach is being successfully employed to understand the increased binding energy of hydrogen in boron-doped carbon, as well as the enhanced reactivity of $Mg(BH_4)_2$ in the presence of Lewis base adducts. In addition, the PNNL team is exploring new ways to tune the thermodynamics in liquid-phase hydrogen carriers by altering the electron density. The overall approach is well focused on addressing important fundamental questions in these systems and optimizing the hydrogen sorption characteristics.
- The approach taken by PNNL is robust and poised to make significant contributions to the HyMARC teams (and seedling projects) by assisting materials developers with solid-state variable-temperature NMR and providing high-pressure and varied-pressure calorimetry.
- The project has demonstrated successful development, implementation, and a combination of advanced computational and experimental (in situ NMR) equipment to allow world-class research.
- This is a strong approach complementary to other work performed in HyMARC. The synthesis, NMR, and theory efforts are well suited for the systems under investigation.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Good progress has been made toward all project objectives in 2017 and 2018. Especially intriguing were the results obtained in the boron-doped carbon studies, where it was shown that the binding energy for hydrogen increases significantly in the boron-doped samples. Although the enhanced reversible physisorption capacities in heteroatom-substituted carbon scaffolds of heteroatoms have been demonstrated in prior work (e.g., Rice University, the National Renewable Energy Laboratory, the California Institute of Technology [Caltech], *Journal of the American Chemical Society* 132 [43] 2010), the present study provides new insight into the enhancement mechanism. Surprisingly, the action of the heteroatom is to facilitate the defect-mediated process that alters the hydrogen binding energies in unusual ways. Clearly, additional work is needed to identify the nature of the defect(s), find ways to controllably generate additional defects, and fully elucidate the mechanism. However, the results obtained thus far are provocative, and they could provide new insight into possibilities for tuning the hydrogen binding energy in carbon materials.
- The project's research has the following accomplishments:
  - It provides an understanding of shuttle boranes and their impact on kinetics for seedling teams.
  - It supports computational work with a post-doctoral researcher who examined boron-doped coronene.
  - It provides an understanding of the addition of tetrahydrofuran (THF) in lowering the melting temperature for $Mg(BH_4)_2$.
  - It provides an understanding of the formation of $Mg(B_3H_8)_2$ in support of seedling projects.
- There is an outstanding advancement in the understanding of hydrogen physisorption on doped carbon, the effect of THF and sorption properties of $Mg(BH_4)_2$, and hydrogen uptake and release from borohydrides, as well as the development of methods to predict hydrogenation enthalpies of liquid carriers.
- A good list of accomplishments was provided. The project team followed stated goals. The liquid-phase hydrogen carrier work is also headed in a positive direction.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- Extensive collaborations are positively affecting all research and development (R&D) areas in this project. The scope of the technical effort is augmented significantly by the experience, expertise, and resources offered by those collaborations. The collaborative work is well coordinated and managed and is accelerating progress in all aspects of the project.
- The PNNL team has demonstrated collaborations with other HyMARC teams; however, there appears to be limited collaboration with seedling projects.
- The consortium collaborates with high-ranking and world-leading national and international research groups.
- The team collaborated well with other laboratories and peers.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is focused on issues that are directly aligned with the goals and objectives of the DOE Hydrogen and Fuel Cells Program. The importance of bringing additional chemistry expertise to the consolidated HyMARC/Hydrogen Storage Characterization Optimization Research Effort (HySCORE) consortium cannot be overstated. The PNNL team will undoubtedly provide the consortium with valuable chemistry expertise and insight that will be needed in the expanded program.

- The computational and experimental work has significant impacts on the HyMARC portfolio. The usefulness of the contributions of PNNL, as one of the core groups providing solid-state NMR capabilities, is clear.
- The impact of using NMR and theoretical approaches, along with standard analytical capabilities, has been the strength of the team. They have identified important fundamental questions and provided well-organized results.
- The team has developed and leveraged unique capabilities to assist materials developers.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The proposed future work is a straightforward and sensible extension of prior work. It is hoped that the boron-doped carbon effort will include a more detailed investigation of the nature of the defect responsible for enhancing hydrogen sorption rates—it is unknown whether this is the same process operative in N- and P-doped carbon. This may involve the participation of other members of the consortium or seedling projects with expertise in solid-state defect generation and characterization. The future work on adduct-enhanced reactions in complex hydrides will, one hopes, include a description of the dependence of reaction kinetics on adduct concentration. This should provide useful information to aid in the elucidation of the enhancement mechanism. Overall, the proposed future work generally addresses important questions. This project will be a valuable addition to the consolidated HyMARC effort.
- Boron-doped carbon, complex hydrides, and hydrogen carriers are in the future scope. Good empirical ideas are backed by some good theory work, making this a strong effort in adding a systematic thought process to advancing state-of-the-art technology.
- The project maintains its future aim of understanding, predicting, and improving physisorption materials as well as hydrogen carriers. In the field of complex hydrides, the new field of liquid-phase complex hydrides will be investigated.
- The proposed future work builds on the past success. Including at least one other interaction with seedling projects would be useful for future work developments. There is nothing to add; the project is heading in the right direction.

Project strengths:

- The project is well organized and uses the strengths of the technique without trying too many experimental methods to answer the questions. It has a very meticulous approach, and the addition of theory made the fundamental connections strong. A lot of interesting mechanistic insights are involved in the hydrogen cycling in these materials. A good baseline understanding will be available from the team. A good collaboration strategy and links to other activities by peers are notable.
- The project addresses fundamental research, which aids in greatly enhancing the current understanding of hydrogen storage systems. For example, the researchers used 50% C-B-N and demonstrated that defects form and that hydrogen associates with these defects. Likewise, the project has addressed the formation of $B_{10}H_{10}$ phases. Another valuable contribution is the idea that the adducts act as a shuttle for boranes and impact kinetics (with seedling project collaborators).
- A strong R&D team using sophisticated diagnostic capabilities is conducting this project. Extensive collaborations are supporting the core effort. The team brings valuable chemistry expertise and insight to the consolidated HyMARC activity. The work on hydrogen carriers will be especially important as the overall hydrogen carrier initiative receives greater attention in the new consortium.
- Within the project, world-class instrumentation and capabilities are developed and successfully utilized to gain a better understanding of and improve hydrogen sorption properties of the most promising material classes of today.

Project weaknesses:

- There are no project weaknesses.
- No major weaknesses are apparent. A minor issue continues to be the same as the one pointed out last year concerning the Mg-borane–etherate work. It was suggested in the prior review that measurements of reaction rate as a function of ether concentration (especially at sub-stoichiometric levels) might provide important insight into the rate enhancement mechanism and the changes in reaction products. The team stated that it was important to do that work, but it is not apparent that the study has been done. A renewed effort to explore the etherate concentration dependence, and to determine how the results affect the understanding of the reaction mechanism, is recommended.
- The weakness is minor. The work proposed seems to be playing it safe and lacks the excitement of discovery. A little bit higher risk-taking and the inclusion of new ideas could improve the impact of the work and explore more uncharted territory. For example, the team is not utilizing the full strength of NMR. Much greater insights are available through 2D NMR and cross-polarization experiments coupled to theory. The theory work is mostly used for thermo-kinetics, and not in designing better experiments. Better integration of the parts will make the project more novel and impactful. These steps are within the team's expertise and experience.
- Perhaps additional interactions with (at least one) other seedling project(s) would prove beneficial.

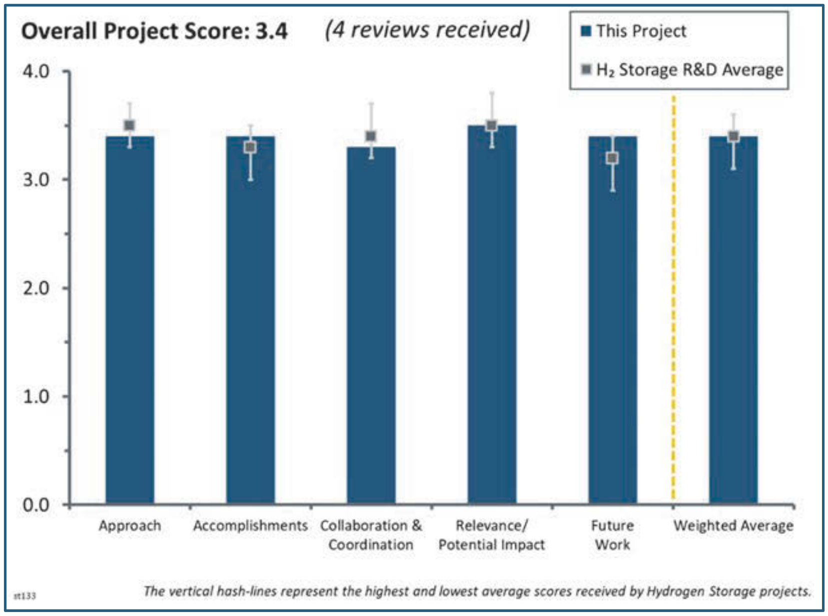
Recommendations for additions/deletions to project scope:

- This is a very good project. The team should go forward in combining excellent experimental and computational capabilities to help materials developers understand and improve their materials' performances.
- The scope is appropriate. No addition to or deletion from this project is requested, only better integration and higher-risk ideas that need to permeate across the board to improve the impact of the work and generate potential breakthroughs.
- The work on boron-doped carbon might be extended to include N- and P-doped materials. It is unclear whether the same defect-mediated processes are operative in those cases. Understanding the roles played by those "dopants" might allow a more general description and model to be formulated. Also (this may be a crazy idea), the team might consider ways to introduce active defects in a controlled way without the possible confusion arising from chemical doping (e.g., inert gas, carbon ion implantation, or something else entirely). That might help to clarify the mechanism.

Project #ST-133: Hydrogen Materials—Advanced Research Consortium (HyMARC): Lawrence Berkeley National Laboratory Technical Activities

Jeffrey Long; Lawrence Berkeley National Laboratory

Brief Summary of Project:



This project is part of a collaboration between national laboratories to develop new characterization capabilities to investigate the properties of promising new hydrogen storage materials. The project works in coordination with the Hydrogen Materials—Advanced Research Consortium (HyMARC) core team. Researchers will also validate new concepts for hydrogen storage mechanisms in adsorbents and provide accurate computational modeling for hydrogen adsorbed in porous materials. Specifically, Lawrence Berkeley National Laboratory (LBNL) is developing in situ infrared (IR) spectroscopy as a tool for characterizing emerging hydrogen storage materials, as well as metal–organic framework (MOF) materials that will allow for more than one hydrogen molecule per open metal site, which will increase hydrogen capacities for sorbent materials.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The principal investigator (PI) and his team have formulated a coherent, rational, and creative approach to addressing the formidable barriers to producing MOFs that adsorb hydrogen at high capacities (multiple hydrogen binding sites) and with enthalpies in the optimal range for hydrogen storage applications. Building upon the successes obtained in prior work (most notably, the synthesis of an MOF with two hydrogen molecules per metal cation and record-high adsorbent uptake at ambient temperature and 100 bar pressure), the approach in 2017–2018 involved the search for an MOF system capable of binding more than two hydrogen molecules per cation site and a hydrogen adsorption enthalpy in the optimal range (-15 to -25 kJ/mol) for hydrogen storage applications.
- The LBNL technical approach is meritorious. The goal is to double storage capacity at 100 bar fill pressure in sorbent materials by tuning binding energies and adding more than one hydrogen atom per metal site. Another feature of the work is the development of in situ IR as a major tool (which will also be available to the seedling projects and other HyMARC laboratories).
- The project has a very well organized objective and approach. The polarization approach with metal cations increases binding energy. A new adsorbant design can help with incremental improvements. The in situ IR is a valuable tool that can operate in an important pressure–temperature range. The experimental results are well connected to the Co/Ni systems. The project sets the enthalpy target and provides good mechanistic insight.
- This is an interesting approach. However, not only is the uptake per liter important (page 5), but so is weight. Ni is a heavy element. Therefore, it is questionable whether the gravimetric storage capacity would be acceptable for such a system.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Impressive and noteworthy results were obtained on synthesis of a promising MOF–metal cation structure capable of adsorbing hydrogen with optimal enthalpy, as well as on identifying and synthesizing promising structures capable of binding more than two hydrogen molecules per metal site. Specifically, the team was able to synthesize and perform structure determination on the first MOF with open V^{2+} sites. The high-surface-area MOF has an adsorption enthalpy in the optimal range. The team also synthesized other structures (e.g., Fe- and Co-CPF-5) with the potential to bind three hydrogen molecules per metal site. In addition, in ongoing theory work, density functionals to model hydrogen adsorption and storage capacities were developed. Results in these areas are advancing state-of-the-art physisorption materials for hydrogen storage; the project is on pace to meet the overall project objectives.
- The project's accomplishments are listed and are in line with the proposed activities and milestones. The V^{2+} MOF with reasonable binding energy is quite promising. The theory seems to be lagging in providing insights on diffuse reflectance infrared fourier transform spectroscopy (DRIFTS) and other observables.
- The development of the DRIFTS instrument is a good achievement. Successful synthesis of V-MOF is very good. Demonstrating two MOFs with high adsorption enthalpy values is a very important result and should be validated.
- The in situ IR data are unique and valuable. The potential found in this approach is clearly demonstrated.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- Collaborations with researchers in the Hydrogen Storage Characterization Optimization Research Effort (HySCORE) and HyMARC are enhancing the core project. Most notable support from collaborations is evident in materials and process characterization and theory. The collaborative efforts are well coordinated with the core project work and are facilitating rapid progress in all areas of the project.
- Unique tools are being developed and will be made available for other HyMARC teams and seedling project researchers.
- The team worked with other laboratories and partners.
- The number of additional collaborations should still be increased. Important findings of high adsorption enthalpy should be confirmed experimentally by other research groups outside the project team, as well.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project directly supports the goals and objectives of the DOE Hydrogen and Fuel Cells Program (the Program). The project is closely aligned with Program needs and is an important element of the overall HySCORE/HyMARC research and development (R&D) activity.
- The results are promising. Some of the open questions need to be answered, and the theory effort needs to approach the high-pressure hydrogenation question before the impact of the work can be fully realized. The doubling of hydrogen storage capacity will be impactful and will bring MOFs back into serious consideration. Nevertheless, the current results are exciting and will provide fundamental insights for new types of MOFs. The metalation and metal exchange effort also shows strong progress. However, some key challenges remain. The theory effort was successful in benchmarking density functional theory (DFT) functionals. The identification of B97-D3 with Becke-Johnson's approximation is a nice result. It will save time that would otherwise be spent exploring more expensive methods.
- The IR instrument has potential to have major impacts. The discovery phase of high-surface-area sorbent materials with two hydrogens per metal site is also promising.

- This project fits with the Program's goals and objectives.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- This project is scheduled to end on September 30, 2018. The future work is clearly stated and builds upon the solid results obtained earlier in the project. The success demonstrated in prior work inspires confidence that the future work will also be successful and impactful. Finding conditions that promote complete activation of the V-MOF, and the successful search for frameworks with sites capable of multiple hydrogen binding, are critical aspects that will require special emphasis. In addition, a careful examination of the potential of MOF-based systems to meet overall DOE objectives needs to be conducted.
- The plans are consistent with previous work. The utilization of lattice Boltzmann simulations to model the storage performances is an important development that should receive focus.
- The planned work is excellent and a good continuation of the effort in more exciting directions. Theory for multiple hydrogen adsorption and polarization effects will be important. The group seems to ignore dynamics of MOFs and their changes with temperature. Overall, the project is moving into a more exciting phase.
- The proposed future work is well in line with prior discoveries.

Project strengths:

- The PI and the core project team are working at the forefront of research on advanced physisorption materials for hydrogen storage. The LBNL core team and collaborators within HySCORE and HyMARC, as well as associated universities, have experience and expertise in all relevant areas of the synthesis, characterization, hydrogen sorption measurements, and theory needed for this ambitious project. A coherent and well-formulated approach is in place, and solid results in all areas have been obtained. This project is a vital element of the HySCORE/HyMARC activity and is an important component of the overall Program R&D portfolio.
- The overall strength is in the very well-defined objectives and approach. This project has strong fundamentals and a good synergy with theory. The new MOFs and DRIFTS results are encouraging. The synthesis effort is also working well to make good candidates.
- The project provides two clear contributions: in situ IR and the discovery of MOFs that contain more than one hydrogen per metal site.
- The combined experimental–computational approach is praiseworthy.

Project weaknesses:

- In the Argonne National Laboratory systems analysis project presentation (ST-001, Ahluwalia), the PI showed (on slide 14) that even in the most optimistic case of four hydrogen molecules per metal cation, the theoretical uptake of hydrogen (at 25°C, 100 bar) is still a factor of two lower than the value needed to reach the system target. Even though excellent progress has been made in the present project, it seems the Ahluwalia predictions may suggest that the MOF approach is essentially a non-starter. A candid and thoughtful assessment needs to be made by the PI and consolidated HyMARC team.
- The extraction of thermodynamic variables from the in situ IR data could be a stretch. Particularly, the data on slide 12 of the presentation show that enthalpy and entropy appear to vary widely with the selected temperature range. Careful baselining work (on systems with known thermodynamics) should be undertaken to establish the use of IR intensity to extract thermodynamic data.
- The theory effort has not supported the experimental work closely. Specifically, much of the work on predicting candidates and variations could use a more high-throughput DFT using the reasonable performance of DFT-D2(BJ) functional. Also, it remains to be seen whether this functional has such a good performance across the board. More effort needs to be devoted to multiple hydrogen molecules and understanding bonding, polarization, and dynamics. More complex calculations of phonons, the effects of anharmonicity, and the predictions of the spectra could be helpful in the future to build the capabilities in a synchronous fashion.

- The group should also aim for a critical evaluation of the potential of characterized and developed MOFs. Important findings should be confirmed by external groups.

Recommendations for additions/deletions to project scope:

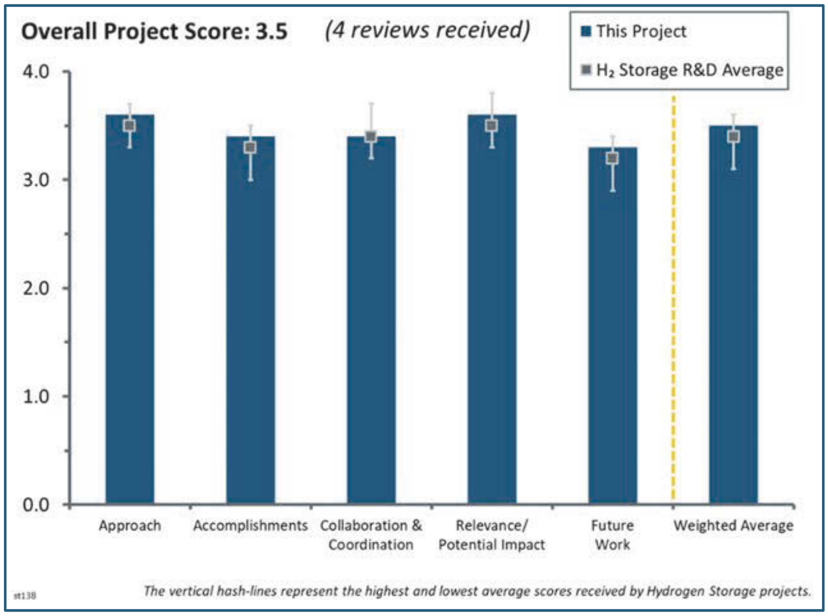
- The scope is well defined. The addition of ab initio molecular dynamics could be instructive in how to stabilize these MOFs in higher-temperature/-pressure conditions and with multiple hydrogens bound to a single site.
- A critical analysis of the materials under investigation for their potential to fulfill the DOE targets and goals should be part of the project. High adsorption enthalpy values should be confirmed by external groups.
- The project is scheduled to conclude on September 30, 2018. There are no recommendations for changes in the project scope for the remainder of the activity.

Project #ST-138: Hydrogen Materials—Advanced Research Consortium (HyMARC) Seedling: Development of Magnesium Boride Etherates as Hydrogen Storage Materials

Godwin Severa; University of Hawaii

Brief Summary of Project:

The objective of this project is to synthesize and characterize magnesium boride (MgB_2) etherate hydrogen storage materials that are capable of meeting the U.S. Department of Energy's performance targets. The project will synthesize MgB_2 etherates using ball milling and heat treatment techniques, study hydrogenation of the materials using variable pressure and time, study and optimize hydrogen cycling of the materials, and develop theoretical models.



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This project is innovative and important. It demonstrates that the hydrogenation of MgB_2 is enhanced significantly by the presence of etherate adducts. The approach in fiscal year 2017 and 2018 extends the initial study to include the synthesis of MgB_2 etherates by ball milling and heating from the reaction of MgB_2 with ethers and other additives, the comprehensive characterization of the MgB_2–ether composite, and the demonstration of dramatically improved hydrogen uptake in the modified MgB_2 materials. In addition, in collaboration with the Hydrogen Materials Advanced Research Consortium (HyMARC), at the Lawrence Livermore National Laboratory (LLNL), ab initio molecular dynamics (MD) simulations were used to identify how the coordinating species perturb the MgB_2 structure and lead to enhanced hydrogenation rates. The overall approach is straightforward and is keenly focused on overcoming the kinetic and thermodynamic barriers for hydrogen sorption reactions that exist in this promising material.
- This is an interesting and innovative project. The $Mg(BH_4)_2$ ammoniates and etherates are promising systems with kinetic challenges. The research is driven by the hypothesis that MgB_2 is destabilized by the ether coordination. The team attempted to lower the MgB_2 hydrogenation pressure from 900 bar to 700 bar. The project is in the initial stages. The plan is well organized and commensurate with the team's capabilities and background.
- The approach is clearly defined: to examine etherate–MgB_2 for hydrogen uptake and to extend the mechanism to other modified MgB_2 materials.
- This project has very good results. However, the check to see whether at least some reversibility is given should have been done at the beginning. Long-term cycling is scheduled for the end of the project—there is no doubt, but at least two cycles should have been tried already, since the start date was October 2016.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Good progress was made in several areas. Most notable was the observation that the kinetics for hydrogenation were greatly improved in the MgB_2–tetrahydrofuran (THF) composite system compared to bulk MgB_2 (hydrogen uptake at 300°C and 700 bar versus 400°C and 900 bar). Moreover, it was shown that the effect was not limited to etherates. Proprietary work has shown that other additives also produce “THF-like” effects. The MD simulations suggest that the additives may destabilize the surface boron structure, thereby creating structural defects that could facilitate hydrogenation. As pointed out in the DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review last year, it would be helpful to experimentally determine the dependence of the rate enhancement on the concentration of the etherate (and/or proprietary additive), especially at sub-stoichiometric concentrations. Those findings could have important implications on the mechanism for enhanced hydrogen uptake.
- The progress made so far is reasonable. The project team claimed to have overcome a major barrier. This data was not shared, nor were the caveats presented. Overall, the key hurdles are next in the plan for Year 2. The progress is reasonable or very good, depending on the high-pressure hydrogenation results.
- This project has excellent results and achievements. It would have been outstanding if the project team could have shown that the effect of the X or THF is maintained after the first cycle without new ball milling.
- The interactions with other HyMARC projects are clear (both computational and experimental).

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- Collaboration with the LLNL theory group was important for providing an initial understanding of the structural changes that could occur in MgB_2 in the presence of etherate adducts or other additives. Likewise, the collaborations with HyMARC/Sandia National Laboratories and the National Renewable Energy Laboratory and Pacific Northwest National Laboratory on high-pressure hydrogenation and the characterization of reaction intermediates and products, as well as the identification of desorbed gas species, have significantly accelerated project progress.
- It is via collaboration (computationally) that other materials that imitate the behavior of the etherate adducts for MgB_2 can be evaluated based on their enhanced hydrogen uptake. X-ray absorption spectroscopy (XAS) will be tremendously useful in validating the suggested mechanism of B-B bond-breaking.
- Collaboration should be easy for the project team because of the members’ well-known background in this domain. Some collaboration on theory and characterization was reported. This seems reasonable for the current stage of the project.
- This project consists of very good collaborations; the LLNL collaboration concerning the MD simulations is especially straightforward. Unlike the other projects, there is no mention of international collaborations.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The $MgB_2/Mg(BH_4)_2$ system is one of the most promising candidates for a practical hydrogen storage system. However, significant barriers to kinetics/rates and reversibility/cycling issues have made the early adoption of this material especially problematic. Through the creative use of additives and adducts to modify reaction rates and pathways, this project is improving the prospects for the Mg–borohydride system in practice storage applications. Overall, this project is well aligned with Program goals and objectives.

- Solution variants of this problem have been explored. However, for solid-state conditions, the role of sub-stoichiometric presence of ethers could open up new possibilities for improving kinetics or lowering hydrogenation pressure. This project could be very impactful.
- Borohydrides are one of the most promising classes of materials for hydrogen storage. Reversibility remains an issue. The pursuit of the adduct–MgB_2 to understand how to drive the reverse reaction is a clever approach and is very impactful.
- If successful, the project could have an enormous impact on hydrogen storage materials development and technologies.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The future work capitalizes on past successes and is reasonable.
- The proposed future work is reasonable and on track.
- The future work follows naturally and directly from previous results and the research and development directions established in prior work on the project. However, the statements concerning specific areas are very general/vague, for example, "synthesis of modified Mg-boride materials"; "optimize MgB_2-X-THF system"; in terms of computations: "effect of additives on hydrogenation." Elaboration and clarification of what will actually be done in each of these areas would have been helpful and would inspire confidence that the future work has been carefully formulated. In addition, as pointed out last year, measurements showing the dependence of the hydrogenation rates on the additive concentration (especially sub-stoichiometric concentrations) are necessary. This information could provide important insight into the overall mechanism.
- The first hydrogen cycling experiments are urgently needed to evaluate the real potential of project outcome. This is currently the most important aspect and should be performed even before the long-term cycling experiments.

Project strengths:

- This is an innovative and novel project that addresses a critical DOE need. The core team at the University of Hawaii and collaborators in the HyMARC consortium bring considerable expertise, experience, and resources to the challenging problems addressed in this work. More generally, the principal investigator and his coworkers are providing the HyMARC team with much-needed chemistry expertise. This will be increasingly important as the technical effort in the consolidated HyMARC consortium expands into new topical areas requiring more extensive chemistry knowledge and intuition.
- The project's goals are noteworthy. The fact that progress is being made in understanding the mechanisms for hydrogen uptake by the etherate–MgB_2, and that these ideas are being used to optimize and develop new material systems, means that the overall project is moving the bar forward for hydrogen storage materials.
- The project is hypothesis-driven and innovative. The team is engaged in exploring modeling for explanations and other experimental capabilities to strengthen the mechanistic insights. This is definitely a good seedling project and supports innovation in storage research.
- This project utilizes a new approach to alter the thermodynamic properties of complex metal hydrides, which is very good.

Project weaknesses:

- The weakness of this project would be minimal if the lowering of pressure with reasonable hydrogenation kinetics was demonstrated. Some further characterization could be helpful, such as engaging in mesoscale imaging (a HyMARC capability) to observe partially hydrogenated MgB_2 grains. It will also be important to map the morphology in the starting materials and through different stages of cycling. This will be explored later in the year and hopefully will be clearer in next year's review.
- Although the modified MgB_2 system has been vastly improved, a wide gap remains between the current state of the art and the DOE targets. It is not obvious that incremental improvements (e.g., different

additives/catalysts, more detailed characterization) will be effective in bridging that gap. At some point in the not-too-distant future, a candid and thoughtful assessment of the prospects for this system vis-a-vis DOE targets will need to be made.

- The whole project currently hangs on the possibility of cycling.

Recommendations for additions/deletions to project scope:

- Changes to the scope are not necessary, since the project is making progress and is close to an important milestone.
- A study demonstrating the dependence of the hydrogenation rate on etherate (and/or other additive) concentration (especially at sub-stoichiometric levels) is necessary.
- Cycling of the materials should now be the top priority.

2018 – Fuel Cell R&D
Summary of Annual Merit Review of the Fuel Cell R&D Sub-Program

Summary of Fuel Cell R&D Sub-Program and Reviewer Comments:

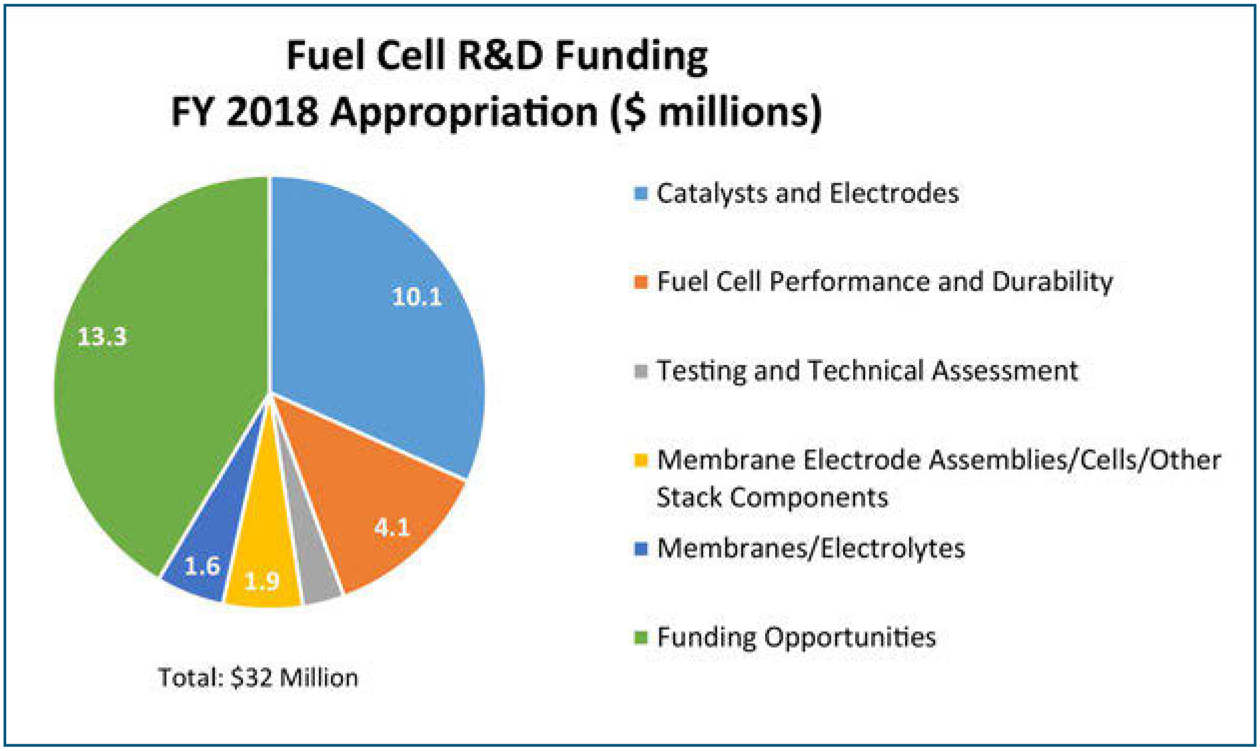
The Fuel Cell R&D sub-program includes a diverse portfolio of fuel cell technologies to enable low-cost, durable, and high-performance fuel cells. Early-stage research and development (R&D) areas in 2018 include catalysts and electrodes, membranes, fuel cell performance and durability, and assessments. Catalyst and electrode R&D comprises efforts on development and utilization of low-platinum-group-metal (low-PGM) and PGM-free catalysts; the latter area focuses on work by the Electrocatalysis Consortium (ElectroCat). Membrane R&D includes polymer electrolyte membranes (PEMs), as well as alkaline membranes. Fuel cell performance and durability is the purview of the Fuel Cell Performance and Durability Consortium (FC-PAD). The Fuel Cell R&D sub-program also includes fuel cell system modeling and analysis, as well as efforts to develop components for unitized reversible fuel cells.

The Hydrogen and Fuel Cells Program (the Program) reviewers noted that the Fuel Cell R&D sub-program has a comprehensive and well-balanced project portfolio. They agreed that the general focus of the various initiatives are in line with the fuel cell industry's long-term needs and address primary issues and opportunities (especially in achieving PEM fuel cell cost reduction with low-PGM catalysts). Program reviewers also specifically noted that the consortia approaches with ElectroCat and FC-PAD are managed well and are the best way to help advance industry and meet future work targets, and should continue to focus on materials properties work in regard to fuel cell catalysts. Reviewers noted that the sub-program needs to do more basic research to make more progress year-over-year in meeting performance goals, especially in terms of the durability technical targets. The sub-program was encouraged to continue to support the approach and collaboration of individual consortium projects. Reviewers stressed the importance of projects focusing on promising concepts such as carbon supports and low-PGM catalysts as crucial components of the pre-commercial R&D portfolio aimed at cost reduction. Reviewers noted some projects, such as reversible fuel cells, represented a low chance of commercialization based on the state of technology. One Program reviewer also noted that projects within the sub-program are relatively small on average compared to similar projects in other countries. Project reviewers were also impressed with specific project-level highlights and accomplishments, as detailed in the project review reports that follow this introductory summary.

Fuel Cell R&D Funding:

The Fuel Cell R&D sub-program received $32 million in fiscal year (FY) 2018. The sub-program focuses on early-stage applied R&D to reduce fuel cell costs and improve performance and durability, as depicted in the figure below. The funding is expected to achieve increased activity and utilization of low-PGM catalysts, PGM-free catalysts for long-term applications, ion-exchange membranes with enhanced performance and stability at reduced cost, improved integration of catalysts and membranes into membrane electrode assemblies (MEAs), and advanced fuel cell performance and durability. Future work is expected to focus on meeting performance, cost, and durability targets for fuel cells with continued work through the consortium approach, further reducing PGM content in catalysts, and expanding the knowledge base to advance fuel cell performance and durability. R&D will also focus on innovative concepts for reversible fuel cells to provide easily dispatchable power and flexibility to address resilience and grid/microgrid needs.

Twenty-eight projects were reviewed, receiving scores ranging from 2.8 to 3.5, with an average score of 3.16. Each of the following project reports contains a project summary, the project's overall score and average scores for each question, and the project-level reviewer comments.

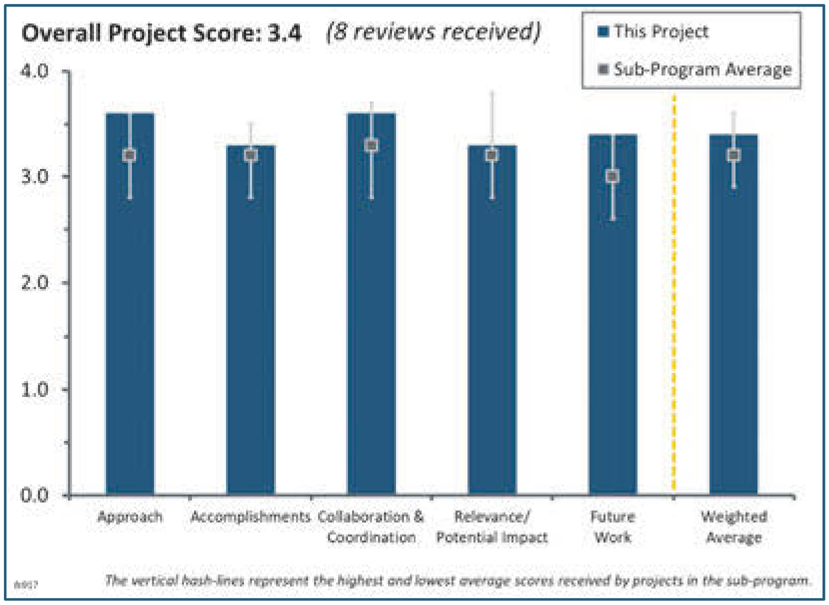

Fuel Cell R&D Funding
FY 2018 Appropriation ($ millions)
10.1
13.3
4.1
1.6
1.9
Catalysts and Electrodes
Fuel Cell Performance and Durability
Testing and Technical Assessment
Membrane Electrode Assemblies/Cells/Other Stack Components
Membranes/Electrolytes
Funding Opportunities
Total: $32 Million

Project #FC-017: Fuel Cell System Modeling and Analysis

Rajesh Ahluwalia; Argonne National Laboratory

Brief Summary of Project:

The objective of this project is to develop a validated system model and use it to assess design-point, part-load, and dynamic performance of automotive and stationary fuel cell systems. Argonne National Laboratory (ANL) will support the U.S. Department of Energy (DOE) in (1) setting technical targets and directing component development, (2) establishing metrics for gauging progress of research and development (R&D) projects, and (3) providing data and specifications to DOE projects on high-volume manufacturing cost estimation.



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The modeling methodology and procedures are highly developed and thoroughly implemented in this project. The team is also very experienced and responsive to addressing key issues with fuel cell components and materials development. Results have been continually refined to reflect identified issues.
- This work is highly relevant to the DOE technical targets and provides a much-needed stack/system element to help ensure the fundamental materials research is moving in the right direction.
- The approach of the project is technically sound and is providing answers to pertinent questions about the fuel cell system design options available.
- The approach involves development and refinement of a polymer electrolyte membrane fuel cell (PEMFC) system model, as well as use of the model to evaluate design choices. The model is being validated using performance data from ANL and various partners. The approach of investigating various design options and using modeling to predict performance and cost makes sense and is helpful.
- The team uses a well-established design for manufacture and assembly (DFMA) technique, combined with technical input/feedback from multiple project lead investigators, developers, suppliers, and original equipment manufacturers (OEMs) to provide a solid estimate of fuel cell system (FCS) projected costs. In addition, the team pulls on experience performing FCS cost studies extending over roughly a decade.
- ANL developed a validated system model, which allows DOE to guide component targets and project success, and allows Strategic Analysis, Inc. (SA) to estimate the high-volume manufacturing costs.
- The Fuel Cell Technologies Office (FCTO) should have a system-level model to provide inputs into other necessary projects (e.g., cost projections), as well as to inform DOE and others of state-of-the-art (SOA) status.
- The principal investigator (PI) is very knowledgeable in the field, and the approach was well-thought-out.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- In fiscal year (FY) 2018, design choices involving system operating pressure, humidification, and system controls for freeze, start/stop, and idle operation were evaluated. Since much of the existing knowledge in these areas is company proprietary, little is known in the research community, and this project is making a meaningful impact by illuminating these issues and building understanding that will inform R&D decisions.
- Very good progress has been made. It would be good to see more emphasis on incorporating low-electrochemical-surface-area (low-ECSA)/low-roughness-factor catalysts into the model (impact on high-current-density performance).
- Accomplishments are relevant, and the team provides excellent data. It will be interesting to see model validation to give further support to this effort.
- The project showed nice accomplishments this year, in particular regarding the idle state and shut down strategies.
- The PI incorporates SOA materials into the model and provides relevant feedback regarding the impact on FCS operation.
- As usual, many additional good results have been accomplished in the past year.
- The team consistently meets the project goals. As an analysis of the status, it does not directly contribute to advancing the Hydrogen and Fuel Cells Program (the Program) goals, except in terms of assessing progress toward the goals and a modest level of guidance on sensitivities and potential pathways to approach the long-term goals.
- This project has been operational for circa 15 years and has been very helpful in defining issues and progress with detailed fuel cell technology. However, it is not clear whether recent results are being independently validated or incorporated by either other DOE-funded projects or industry. It now appears that current efforts are more or less minor tweaks to existing concepts and systems.

Question 3: Collaboration and coordination

This project was rated **3.6** for its collaboration and coordination with other institutions.

- This project has a long history of productive interactions with other organizations concerning fuel cell technology issues. Apparently, the team intends to continue this in the future assessments, including activities with the Fuel Cell Consortium for Performance and Durability (FC-PAD).
- The team is collaborating extensively with multiple partners to guide model development and provide validation data. The collaboration with SA is critical for guiding SA’s cost projections.
- This project is engaged with many academic and industrial partners. Overall, there is excellent collaboration.
- The team has consistently had excellent collaboration with various suppliers, developers, project lead investigators, and OEMs. If there were any wish, it might be to have more input from international-based suppliers, OEMs, and organizations.
- This project has considerable collaboration that provides useful and significant data to the project.
- The team has impressive engagement with many OEMs, component suppliers, and others.
- Project collaboration involves industry, universities, and government entities inside the United States and internationally.
- The level of collaboration and coordination appears appropriate for this type of project. Collaboration with FC-PAD and the Electrocatalysis Consortium (ElectroCat) should be enhanced, in particular to integrate durability data from single cells and stacks and performances from new catalysts.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project provides much useful and important information surrounding cell, stack, and system design trades. This work has the potential to increase the speed at which system trades can be performed, saving money for those that leverage the information.
- This project is relevant in that the Program requires an effective tool to assess progress toward Program goals, and also to supply recommendations on how to approach the goals and targets. This project provides this function and consistently meets project goals. The project also is charged with supplying guidance on sensitivities and potential pathways to approach the long-term goals. The team may want to expand opportunities here (i.e., determine what areas should be focused on that will have a marked impact on cost reduction).
- The project is relevant in its role of integrating evolutions of component and sub-component performance as system architectures and subsequent system performance. A valuable impact is helping SA better estimate the cost status. However, the impact might be even higher if the model could have been validated at stack and/or system level and not only at single-cell level.
- Examining system designs and modeling the effects of design decisions on performance and cost are helpful for building understanding and informing R&D decisions. Since OEMs are generally secretive about design decisions, it is helpful to have a DOE project investigating this space.
- This work is absolutely necessary, but because of the nature of the work, is not likely (by itself) to result in a significant advance forward. Rather, it helps to guide future work.
- Modeling is an essential component to research and should be deemed necessary.
- The relevance/potential impact of this project is good. However, it is always limited to looking backwards (i.e., it is unclear what the current SOA is). More sensitivity studies of key variables or components (real or hypothetical) should be done to help identify what improvements could make substantial impacts on cost, performance, or durability. The PI says that he assists SA with making these types of sensitivity assessments, but that is limited to cost only.
- While the project continues analyses that relate to PEMFC performance, including some trades and alternative configurations of balance-of-plant components, it is not obvious that any of these will lead to breakthroughs in meeting the DOE targets.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The future work largely continues the current work in refining system design models and providing input to SA. The project will continue to investigate and evaluate new components, including new catalysts and new electrode designs. The proposed work on plates and flow fields could be helpful because flow field design is a poorly understood subject and most R&D work is performed on suboptimal flow fields.
- Selected topics and plans for remainder of FY 2018 are sound continuations of current efforts. The team is including efforts to address performance of lower-content Pt-based catalysts and platinum-group-metal-free (PGM-free) candidates.
- This is an excellent plan forward. It is suggested that ANL add more focus (some was already present) on the impact of low roughness factor on high-current-density performance. Coupling this with anticipated ECSA loss from cycling, it would be helpful to have guidance for a targeted benzyl alcohol catalyst ECSA. Perhaps including a few possible operating modes/system controls, and describing how that would affect the required catalyst ECSA, could help to guide catalyst researchers/funding toward commercially relevant catalysts (e.g., those that meet the ECSA requirement, as opposed to focusing strictly on mass activity).
- The project's future work list appears sound. It is recommended that ANL perform another round of sensitivity analyses to identify remaining low- or mid-hanging fruit to further reduce cost. Perhaps not all the answers lie in power density. It is also recommended that ANL do a similar analysis to that performed here for PGM-free (and perhaps anion-exchange membrane [AEM]) systems. It might be good to learn

what the status of their FCS costs are, as well as what it would take for them to reach the Program targets (or even to be on par with the conventional low-PGM PEMFC system).

- The proposed future work looks to be more of the same, which is good. However, to be excellent, the PI should strive to generate results that could enable making recommendations on the most important improvements to performance (e.g., system size and weight) and durability.
- The proposed future work is in line with the overall targets. Integration of durability aspects and focus on low-volume manufacturing is appreciated. However, some additional points should be investigated: (1) an analysis sensitivity on stoichiometry ratio (in particular at the cathode), and (2) the use of longer-durability testing data (as 100 hours is very short and 95°C is not representative of real life) coming either from FC-PAD or from ANL tests using current automotive durability testing protocols.
- ANL is taking the input from past reviews to help improve the product output. The approach seems sound and is building upon past results and input.
- Future work is clearly listed and is appropriate.

Project strengths:

- The team has excellent continuity, as the team members have been working in this space and refining their modeling techniques for many years. There have been excellent interactions with partners to provide information about design choices and to provide validation data, which is very helpful.
- The team has an extensive history in FCS cost analysis using a well-established DFMA technique, combined with technical input/feedback from multiple project lead investigators, developers, suppliers, and OEMs.
- The ANL team is highly experienced and skilled in performing the analyses of the PEMFC components and systems.
- The project starts at the cell level and moves into the system level, with design trades at each step. This is a comprehensive model.
- The transparency of system-level performance and cost implications of various materials and design options is a strength, as with the collaboration with FC-PAD.
- This is an important project to support FCTO’s overall mission. The work done is rigorous and substantial.
- This is critical work in helping to guide materials-level research.
- The project has positively contributed toward addressing the technical barriers identified by FCTO.

Project weaknesses:

- ANL should seek to do more sensitivity studies to identify what key improvements can enable substantial improvements in performance and durability.
- The project is mostly dependent on patent literature to learn about design choices used by OEMs. Since OEMs are generally secretive about design choices, this is an unavoidable weakness.
- The model should be validated at a stack and/or system level. It is difficult to rely on a model based solely on experimental single-cell testing results and, moreover, using testing parameters that are severe but not representative of real-life trials.
- The project would benefit from more input from international suppliers, developers, and organizations.
- The project modeling could use more validation and predictive capabilities.
- Increased emphasis on Pt dissolution/impact on ECSA would be beneficial.
- While numerous predictions have been made over the years, it is less clear just how thoroughly these have been vetted by commercial developers and users.

Recommendations for additions/deletions to project scope:

- It is recommended that the project continue at the current FY 2018 level of support.
- Another round of sensitivity analysis to identify remaining low- or mid-hanging fruit to further reduce cost should be added. Perhaps not all the answers lie in power density. Perhaps lower-cost steels should be considered, as well as what would enable their use. A similar analysis to that performed here for PGM-free (and perhaps AEM) systems could also be added. It might be good to learn what their status FCS costs are,

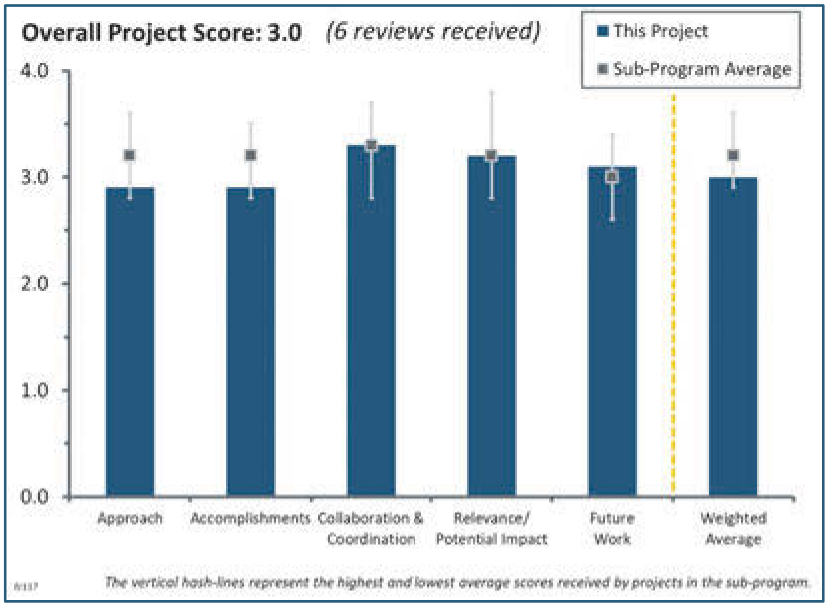
as well as what would it take for these systems to reach the Program targets (or even to be on par with the conventional low-PGM PEMFC system).

- ANL should investigate the impact of operating modes on Pt dissolution. In general, it seems Pt dissolution is a far more important concern for OEMs than carbon corrosion (air/air events). Understanding this phenomenon and relating it back to catalyst requirements would be extremely beneficial.
- Automotive OEMs should be persuaded to share stack or system data to validate ANL's model under at least a few key operating conditions, with at least one system-level configuration.
- ANL should seek to do more sensitivity studies to identify what key improvements can enable substantial improvements in performance and durability.
- A more mechanistic approach could better direct research.
- Model validation is part of the proposed future plan.

Project #FC-117: Fiscal Year 2015 Small Business Innovation Research (Phase II Release 2): Ionomer Dispersion Impact on Polymer Electrolyte Membrane Fuel Cell and Electrolyzer Durability

Hui Xu; Giner, Inc.

Brief Summary of Project:



To improve polymer electrolyte membrane (PEM) fuel cell and electrolyzer performance and durability, this project seeks to understand how ionomer dispersion affects electrode structures and PEM fuel cells. Specific project tasks include (1) investigation of ionomer dispersion in a variety of solvents and how those solvents affect ionomer morphology and conformation; (2) analysis of how ionomer dispersion affects the electrode function and structure, including ionomer distribution, catalyst distribution, porosity, and thickness; and (3) evaluation of how ionomer dispersion influences fuel cell electrode performance and durability.

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach is very good, since it includes a good variety of materials and includes both performance and durability assessments.
- The approach is well-thought-out and contributes to the understanding of the electrode structure and deposition on performance. However, the work presented is narrow, as there needs to be a comprehensive evaluation of more than just physical morphological characteristics of electrodes/membrane electrode assemblies (MEAs) on performance as a result of the solvent used for deposition purposes. What is required are the chemistry fundamentals and influence of the solvent at the molecular level on all the elements of the MEA and the electrode itself. Furthermore, once cells are operated, the system becomes 100% aqueous-based, so an important question is how the different solvents used for the deposition process change or affect performance once the entire system is hydrated, because these are water-based processes. Studies need to include the solvent's effect on the carbon supports, the ionomer particles themselves, and the impact on the interfacial region and membrane after rehydration.
- This project has good relevance, as solvent–ionomer interactions are of interest to the industry. However, there are some issues with the project and/or poster:
    - There is no significant electrolyzer work presented.
    - It is surprising there is no water solvent as a comparison or baseline.
    - Some of the data shown are not clear (end-of-test electrodes seem thicker).
    - U.S. Department of Energy high-level targets are presented, but not this project's specific targets or go/no-go decisions.

  Finally, more work could have been done with the project over three years, such as an ionomer-to-carbon (IC) ratio evaluation for select solvents and their impacts on durability. More electrolyzer work (if that is part of this effort) is necessary. The team should take the best solvent system and optimize it for peak performance and durability.

- In general, the approach was to optimize PEM fuel cells and electrolyzer performance and durability in two ways:
  - By adding ionomers to the electrocatalyst layer to optimize three phase contacts (specifically, the ion conductor, electron conductor, and feed gas).
  - By using different liquid "solvents" that evaporate at different temperatures to dictate the physical phase of the polymer N-methyl pyrollidone (NMP, boiling point 202ºC). Typically, a high-boiling solvent brings the polymer (here it is Nafion) over 140ºC, where Nafion undergoes a phase transition from being a fragile and brittle film to a plastic and tough film.

  It is not clear in this presentation how the project addresses additional technical target tasks, such as MEA mechanical strength and durability, as listed in bullets on slide 2.
- The approach is clear and does improve overall understanding of current catalyst layer design parameters. While this work may help to improve durability, gains are likely to be limited (i.e., no fundamental advance is expected).
- The major flaw in the approach is that the ink formulations and drying methods were not optimized for each solvent, bringing into question the universality of the conclusions. A much better approach would have been to conduct a design of experiments where solvent type was one of the factors. The IC ratio was constant for all solvents. The contents of the solids were not disclosed. Also, while some valuable analysis was done on the inks (although more rheological analyses is suggested) and the catalyst layers before and after durability testing, the correlations between fuel cell performance and ink properties are completely speculative, with no mathematical or mechanistic explanation of the results. There was no attempt to answer the question of why the higher boiling solvents supposedly lead to slower particle growth. Measurements of electrochemically active surface area and activity before and after testing were not disclosed, nor was there any attempt to measure gas transport losses. A more fundamental link between the analysis and the results is required.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team effectively met the targets by examining different dispersant solutions of Nafion polymer to alter active layers which have dispersed ionomers, stable electrodes with ionomers, in a processable and scalable way, where most of this is accounted for in terms of the phase transition, which occurs at high-temperature curing of polymers to induce formation of a plastic, tough polymer film in the electrode.
- The lack of optimization work for each solvent system really limits the overall accomplishment of the project. That said, developing a methodology to determine a desirable ink design to achieve optimal performance and durability is a valuable undertaking. However, without coming up with a clear set of design rules, the project results are not universally applicable and can potentially be misleading. A partial set of observations was reported, but there was no clear transferable learning. The authors did well to highlight the downsides of the "preferred" solvents, especially the long drying and mixing times, which make them unattractive low-cost solutions. The most valuable result was the result showing that a relatively small amount of ethylene glycol might be beneficial, thus teaching that investigation of mixed solvent systems may prove fruitful.
- The reported results are quite insightful and valuable, as they shed light on the electrode structure after deposition and the impact of the structure on initial performance. The work on particle size distribution and related data is a good example of progress made in this effort and represents a good starting point. It is not clear, however, how bullet 2 on slide 2 (the Technical Targets) is addressed in this work—a mechanical and chemically stable MEA. The progress reported is focused on ionomer–solvent depositions. Studies need to be performed at a much more detailed level. For example, Nafion-based membranes are exhibiting a much longer life than 5000 hours in non-stationary applications, and have for years. Furthermore, the knowledge and methods for deposition have been developed and used by major commercial suppliers of MEA—hence, it is unclear what is actually new here. The impact after operation for long periods of time in an aqueous environment on the various electrode layers is also uncertain.

- DOE targets are listed, but this project's goals are not listed. Therefore, it is unclear how the project progressed. Good data have been generated, but perhaps analysis has not been done to link the data. The identification of solvent trends could have been pursued more.
- Good progress has been made so far in terms of testing, but so far, the solvent systems have all had a tradeoff in terms of performance or durability; unfortunately, neither can be sacrificed.
- The results are not clearly summarized. For example, the summary states that "ionomer dispersions influence performance." However, the presented results do not indicate that, and when the principal investigator (PI) was asked about it, he stated that there was no performance impact. There is a reported durability impact, but there is no attempt made to summarize this impact in an insightful way. For example, the summary states that "high boiling point solvents greatly improve durability," but this conclusion is not clearly supported. This could readily be done by making a plot of decay (i.e., voltage changes shown in slide 10) vs. solvent boiling point, to demonstrate that this key conclusion is actually supported by the data. Some skepticism of all of the unsubstantiated statements made in the summary seems appropriate, since the statements are not clearly supported and the performance statement is obviously false.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The team collaborating on this project is quite appropriate. All members bring a wealth of experience in not only knowing how to assess the technical parameters of the electrode, but also the knowledge of electrodes in general, in this field. The Oak Ridge National Laboratory (ORNL) team is essential, considering the technical objectives and the focus on the electrode structure and properties; Los Alamos National Laboratory (LANL) and the University of Connecticut (UConn) bring electrochemical know-how and experience.
- Clear contributions were made by all partners. The background experiments for this study were done at LANL, and LANL consultation continued on this project. ORNL's and UConn's main contributions both appear to be in the area of transmission electron microscopy (TEM)/energy dispersive X-ray spectroscopy (EDS) analysis.
- The team partners are complementary and performed their roles well. The dimensionally stable membrane (DSM) was from Giner, Inc., while the ionomer solutions came from LANL. ORNL and UConn contributed to the imaging.
- There is good work by national laboratories on the imaging, which is valuable to this project.
- There are partners, but it is not at all clear what they have contributed to the project—other than UConn, whose activities are actually stated on the acknowledgements slide (TEM/scanning transmission electron microscopy-energy dispersive X-ray spectroscopy [STEM-EDS]). On this slide, the others are simply listed as a "subcontractor" or a "collaborator." What each has contributed should be noted here, at a minimum.
- All project partners appear to be engaged, but it is rather unclear what differentiates UConn's and ORNL's contribution. What capabilities are unique to each institution is unclear.

Question 4: Relevance/potential impact

This project was rated **3.2** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The potential impact is huge. A long-life, reliable, chemically and physically stable MEA is still elusive with reference to durability and cost, depending on the application. The electrode composition and interactions, if better understood, could lead to long-life, low-cost MEAs, as needed for commercial success. A comprehensive understanding of the elements of the electrode and their impact is ongoing—the work by Myers at Argonne National Laboratory and now More at ORNL are good examples.
- The team performed a needed, important, and non-obvious task for making good MEAs when using Nafion membranes. The results can guide similar developments in non-Nafion polymers. The team should publish these results so others are aware of this, in order to help the technical community develop fuel cells and

electrolyzers. The most valuable contribution here is knowledge about "non-obvious processing" steps for making good MEAs.

- This work is relevant.
- This work is important, and useful information will be (and already has been) generated. However, it appears more incremental (as opposed to a true breakthrough) and of interest to current MEA designs. Thus, it is unlikely to greatly help in significantly closing the gaps on any DOE technical targets.
- Performance and durability are obviously very important, but the impact of this work is not clear for multiple reasons:
    - It is not clear what new conclusions have resulted (relative to previous work in this area).
    - The results obtained here are not clearly communicated (i.e., no trends are clearly reported and substantiated).
    - The impact on performance is negligible, and although there is an impact on durability, this project is not providing elucidation into why.
- Ionomer dispersion impact on fuel cell performance and durability is extremely dependent on the selected ionomer and catalyst materials. A project that focuses on a single material set and does not conduct any optimization studies is not very relevant to those looking for guidance on how to design a high-performing, robust MEA. At the very least, such a project should provide design rules of methodologies that MEA developers could apply. In reality, any MEA developer will conduct its own design optimization studies, and this project really does not teach much that can be applied to help with such optimization. Also, the Pt loading used in this project is too high to be of interest for automotive fuel cell applications.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work is reasonable and involves performing TEM of fresh MEAs, compared to decals and decayed MEAs; further testing of the non-aqueous ionomer-based electrode under more realistic accelerated stress testing conditions; exploring state-of-the-art components integrated with non-aqueous ionomers to make low-Pt and high-power MEAs (work to be done in Phase IIB), including high-performance Pt and its alloys and thin membranes (DSMs); and performing scale-up of electrodes (work to be done in Phase IIB). Of the above planned work, there is a need for scale-up and the testing of scale-up as the most important activities. Also, publishing this work in a journal such as *Power Sources* is needed, as a location where developers will learn that this processing is an important goal.
- The future work does sound highly relevant and may result in more meaningful gains in terms of performance/durability.
- Even though the project is complete, some future work was shown. The one valuable set of future work activities was exploring Pt alloys. The other items suggested (such as thin membranes or scale-up) do not add value. Consideration of lower Pt loadings (<0.1 mg/cm^2 Pt) is suggested, as is more than just a single test with a different ionomer.
- The proposed work is not detailed enough. A more fundamental understanding of the interactions of the solvent on the ionomer, membrane, application, and performance should be the primary focus of the next phase of research and development. Questions should be asked related to the preparation history of the membrane, the membrane itself, composition and ion exchange capacity, the method of application of the electrode to the membrane, and the interactions of the solvent with the ionomer, catalysts, and sulfonic acid groups. Even with high Pt loadings on the support, it is still the impact of the solvent on the carbon particle that should be addressed from a deposition and electrode layer characterization perspective. Post-mortems as a function of time should be looked at analytically from a chemical interaction perspective—not just by microscopy and by changes in pol curves.
- The plan is good, but if the execution is the same as in Phase I, then the impact will not be significant.
- The project is completed.

Project strengths:

- The project has a good team with much experience. The potential outcome is quite positive, and the project is starting to look at the ionomer deposition process and the impact on the electrode structure. Giner, Inc.

has the experience in product development from the bench to commercialization—this is very beneficial in focusing the effort.
- Giner, Inc. has assembled a competent team, and the results presented are clear and easy to understand. The TEM/EDS analysis of electrodes is good.
- This is a good topic that does have an impact on both performance (not found here, though) and on durability, which has not been sufficiently explained to date.
- The execution of processing is good, as is the characterization of the results.
- The project contains good data. This was a good opportunity with solvents and included good collaboration.
- This is an important area of work with direct relevance to immediate products.

Project weaknesses:

- The focus is too narrow, and the analyses are not detailed enough. This project does not address all the objectives as listed (at least in this presentation). Knowing that a given deposition process yields good performance is critical and valuable; this work is a start but should have included more comprehensive analyses.
- There is a lack of any optimization work or systematic electrode design, as well as a lack of universality of the approach. The Pt loadings in this project are not forward-looking. No design rules were developed.
- There is limited electrolysis work. Better analysis could further the good data taken. More work and progress could have been made.
- The PI does not appear to be interested in analyzing the data in a way that allows one to draw substantiated conclusions.
- It is unclear how large of an advance in either performance or durability will be achieved by this approach.
- The lack of interpretation and dissemination of the results to date is the weakness of this project.

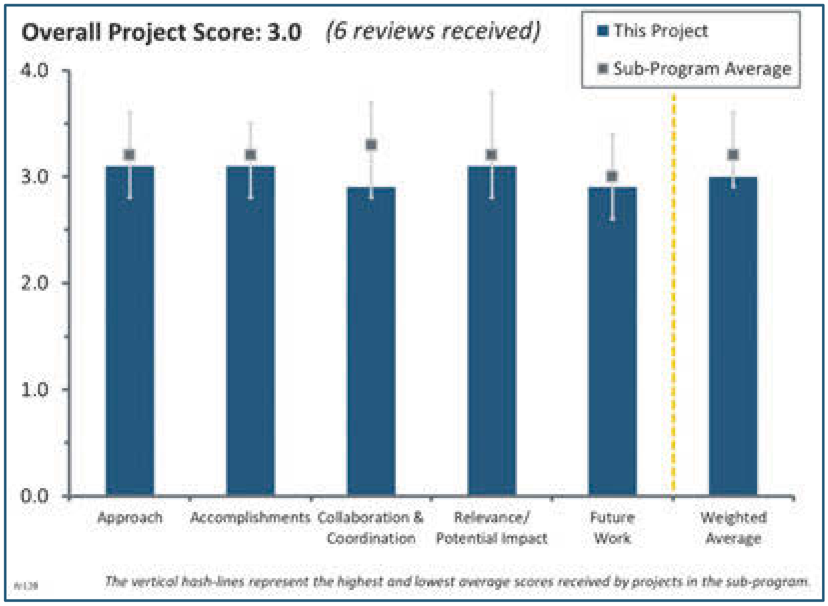
Recommendations for additions/deletions to project scope:

- More comprehensive analytics of the electrode before and after operation is recommended. The cathode is mentioned in this work, but it would be good to know the impact of the anode and cathode in less than 100% relative humidity conditions (as a fuel cell would experience in real-world operations). A broader range of testing conditions is suggested, followed by post-mortems and analyses. Economic estimates of the process based on all the results after the three-year effort should be included if this project receives additional funding.
- More in-depth voltage loss breakdown analysis is warranted on these designs to help with understanding exactly how the different solvent systems are affecting performance/durability.
- It is recommended that the project team do a substantially better job of analyzing the data, such as by making plots to elucidate any hypothesized trends to support key conclusions.
- No deletions are recommended. In terms of additions, developing scale-up and publishing these results are suggested.

Project #FC-128: Facilitated Direct Liquid Fuel Cells with High-Temperature Membrane Electrode Assemblies

Emory DeCastro; Advent Technologies, Inc.

Brief Summary of Project:



Dimethyl ether (DME) is a carbon-neutral hydrogen carrier that can be used both for internal combustion and as cost-effective fuel for auxiliary fuel cell power systems in automotive transportation. This project will demonstrate direct DME oxidation with high-temperature membrane electrode assemblies (MEAs) and a Los Alamos National Laboratory (LANL) catalyst. DME is expected to significantly outperform state-of-the-art direct methanol fuel cells (DMFCs). The project will incorporate the new ternary anode catalyst in gas diffusion electrodes designed for high-temperature MEAs, evaluate performance with two different high-temperature membranes (polybenzimidazole [PBI] and tetrapyridine sulfones [TPS]), and optimize structures and reaction conditions.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- A key metric in this work is Barrier C, related to performance, which is the activity of the high-temperature polymer electrolyte membrane fuel cell (PEMFC) using DME versus methanol (MeOH) as an anode feed and air (or oxygen) as the cathode feed. The team is doing well on this, checking different catalysts and efficiency and power through current-versus-potential (I-V) curves. The challenge for the polysulfone barrier is cost, and Barrier B is associated with catalyst cost; the advantage to cost is simplification (eliminating the reformer), which the team is addressing very well, looking at different materials for anode catalysts and systematically reducing precious metal loading. The durability barrier, Barrier A, is being addressed by the team by examining the temperature stability of two options (PBI and TPS, i.e., pyridine substituted for polysulfone). There could be a good synergy with other workers at LANL looking at the new high-temperature membranes made by Yu Seung Kim et al. Although Advent Technologies, Inc. (Advent) is dedicated to these options, Zelenay is at LANL and may obtain samples for the team. Looking at short-term stability of the DME anode for both the two Advent options and the LANL options seems like a good idea. Another issue is to get some temporal durability data. Although this is application-dependent, it seems wise to screen the membrane by doing conductivity testing (electrochemical impedance spectroscopy [EIS]) over time, testing for a day or so at specific temperatures from the low to the high end of the temperature range. Catalysts should be screened by taking chronoamperograms (current at constant cell potential versus time) under well-defined conditions for at least a day. DMFCs are notorious for high activity for a few hours, followed by rapid decay of anode and anode catalyst in a day or two, followed by very low activity after a week. EIS and chronoamperograms should be done to rate the relative performance of materials and possibly to screen and downselect materials (membranes and catalysts).
- The project approach is innovative: using a fuel cell to oxidize DME at high temperature. However, the advantage, in terms of energy density, of DME compared to hydrogen seems to be outweighed by poor

performance, even at high temperature, relative to PEMFCs. It would be good to know what platinum-group-metal (PGM) loading and performance would have to be achieved to make this more than a niche product for a niche market. Addressing the catalyst and gas diffusion layer (GDL) to improve performance is the right track.
- The project objectives are clearly identified, and the progress to date seems reasonable. However, additional efforts may be needed to characterize the electrochemical performance of the membranes in fuel cells under practical conditions.
- The project is designed effectively to address the barriers such as performance, durability, and cost. This is an incubator project aimed toward DME fuel cells operating at high temperatures. As such, this is a unique project that could not be compared to other similar efforts; however, it is important to mention that the investigators are making significant progress that is in line with previous years of this effort.
- The approach of using a PBI–phosphoric acid membrane is good for using the system under high temperature and thereby harnessing high catalyst activity. However, acid leaching will cause PBI–phosphoric acid membrane conductivity in a direct-water-solution-fed system to change over time, especially under proton flux. This change in membrane conductivity will have an impact on the durability/performance of the system. Under 30 psig backpressure, such leaching will be minimal, but past studies (Plug Power) of PBI–phosphoric acid systems using gaseous hydrogen and air have shown acid leaching/membrane conductivity changes and the need for acid traps to mitigate acid issues. It is not clear that PBI–phosphoric acid is a good separator for such direct-water-fed fuel systems. PBI–phosphoric acid may not be practical for commercialization of a usable system.
- Key barriers have been identified. It is not clear how cost is being addressed, as the PGM loadings for the ternary catalysts are similar to those of the commercial binary catalyst. It is not clear how durability is being addressed (no durability work was highlighted last year or this year), though durability is indicated as a key barrier. The approach appears to focus on optimizing Pt-Ru-Pd, without having clear evidence that Pt-Ru-Pd offers increased activity over commercial Pt-Ru. Analysis of activity on a PGM basis and breakdown of voltage losses appears to be lacking. The project team went through a downselect on membranes earlier but is now suggesting returning to TPS membranes to allow for higher-temperature operation. It appears that some of the requirements were not considered when the downselect was made.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Some very impressive results have been quoted. Meeting and lowering catalyst loading below 5 mg-PGM/cm^2, an order-of-magnitude-lower crossover with DME (6 mA/cm^2) versus methanol (60–120 mA/cm^2), and high short-term power that meets the DOE target of 270 mW/cm^2 were shown at high temperature with the TPS membrane. It is time to begin to screen durability using EIS and chronoamperometry testing, if for no other reason than to rate and to screen materials in a timely way now, before this task is lost, because it may become too difficult to revisit some samples as time goes on. Although it is not necessary, at some point, another possible metric might be to measure relative solubility and/or diffusivity (or the product permeability) of DME and methanol in membranes to see whether this is correlated with the low crossover. This finding might give an easy guide to future development.
- The team has accomplished anode mass activity higher than the DOE target, as well as present anode catalyst mass activity in a DMFC system. The DME crossover target has also been met. DME has lower crossover compared to methanol at 80ºC in a Nafion® membrane because DME has lower solutility in water and also is not a hydrophilic, like methanol. The team did not have much success in reducing the total PGM loading and is not close to the DOE target. Also, the maximum power output is only 50% of the target and lower than the maximum power of a DMFC system. Interestingly, the team used water to evaluate the LANL ternary catalyst, which has the same I-V performance as a binary Pt-Ru catalyst/1.0 M methanol. However, in the present work, the binary Pt-Ru catalyst system worked well with DME fuel, which is contrary to the I-V curve shown in slide 4. The team gave no clear explanation of this behavior. The performance in slide 4 was with direct-fed DME gas, while the team used a DME:water 1:3 solution for the project work. It is not clear why the team decided to change the fuel from DME gas to DME solution.

- Some important progress has been made in synthesis and fabrication of membranes and in characterization of some properties of the membranes under simplified conditions. However, it seems that additional efforts are needed to confirm some key performance indicators, especially under practical conditions for fuel cell operation. The principal investigator's (PI's) company does not have facilities for fuel cell operation/ testing. Thus, closer collaborations with a fuel cell developer (e.g., the national laboratory partner) are vital to accelerate the rate of progress and to validate the technical feasibility of the proposed new high-temperature membranes.
- The project has demonstrated gains in performance and reduced fuel crossover compared to a DMFC. Performance gains have been realized in the past year by increasing operating temperature. However, performance is still far short of targets, with power density less than half of target value. The work to date has not shown a clear benefit of the ternary catalyst composition, and data were not presented in a manner to help separate out activity from transport losses to help evaluate whether the ternary has higher activity than the binary catalyst. There has been little progress since last year in demonstrating the ternary catalyst.
- The project is making progress, as evidenced by met milestones and go/no-go's. However, a lack of targets for alternative fuels for fuel cells means that the project can meet self-set targets with high catalyst loadings. PGM loadings should be more reflective of current PEMFC PGM loadings; otherwise, the cost of these devices does not make them appealing.
- This is the last year of this project, and the investigators made significant progress in demonstrating that DME can be effectively employed at high temperatures. The metrics that have been obtained can justify a strong case for further exploration of the DME concept. The project team was focusing on multi-metallic catalysts and insisted on Pd utilization, although there is no clear benefit to Pd inclusion.

Question 3: Collaboration and coordination

This project was rated **2.9** for its collaboration and coordination with other institutions.

- The team is excellent and complementary. Advent is taking the lead on the membrane and LANL on the catalyst and testing. It might be good to try other LANL membranes from different researchers at LANL, such as Yu Sung Kim, if this is possible. Exploiting LANL testing on EIS and chronoamperometry to screen durability to complement activity testing may be good to help rate and downselect materials. This would be better done sooner rather than later so as to not lose information, as it may be difficult to "revisit" some materials later.
- The collaborator, Dr. Zelenay's team at LANL, has a wealth of experience in DMFC electrocatalysis and systems. This group is the right collaborator for the project.
- The project has new collaborations with two catalyst suppliers to test ternary catalyst compositions. Collaborations within the project appear to be going okay.
- This is a well-coordinated effort among the participants, with clearly defined roles.
- It appears that some collaboration exists; however, coordination between partners could be significantly improved, especially in the area of critical evaluation of the membrane characteristics and long-term stability under practical fuel cell operating conditions.
- The extent of collaboration is not clear. If LANL is making and testing the catalyst, which is the bulk of the results, as indicated in the slide, it is not clear what Advent is doing.

Question 4: Relevance/potential impact

This project was rated **3.1** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This work has its greatest use in portable power: auxiliary power units, portable electronics, scooters, etc. These are needed for a broad spectrum of uses, including military and commercial and emergency power. Developing these markets can be profitable and can stimulate developments in larger applications such as automobiles and heavy vehicles.
- Since the development of high-temperature polymer electrolyte membranes (PEMs) is vital to a new generation of fuel cells, the project aligns very well with Hydrogen and Fuel Cells Program (Program) and

DOE research, development, and demonstration (RD&D) objectives. If successful, the project has the potential to advance progress toward DOE RD&D goals and objectives.
- Overall, using direct-fed DME is expected to have great benefits. The projected source-to-use cost is lower than DOE's target. However, DOE's high-temperature direct DME fuel cell targets are very challenging, and significant technical breakthroughs, especially in catalyst and membrane technologies, are needed to meet these targets.
- DME makes sense as an energy carrier and a fuel. It is not clear how projects directed toward direct liquid fuel cells overall and this project in particular fit into the overall Program. The Program is increasing focus on developing a hydrogen infrastructure, and the fuel cell efforts are moving away from PGM materials to PGM-free materials as catalysts. Direct liquid fuel cells promote non-hydrogen fuels and send the message that hydrogen is not an adequate fuel and alternatives are needed. This is not the message to send when trying to increase acceptance of hydrogen as a fuel and trying to increase hydrogen infrastructure. Direct liquid fuel cells, and this project in particular, utilize PGM-based fuel cells with high PGM loadings. The targets for this project will result in a fuel cell that obtains <0.1 W/mg PGM or requires >10 g PGM/kW, approximately two orders of magnitude more Pt/kW than current PEMFCs. This appears to be at odds with the current direction of the Fuel Cell R&D sub-program that is emphasizing PGM-free catalysts and phasing out low-PGM catalyst work. It does not seem logical to carry out work on high-PGM-loading direct liquid fuel cells when low- and ultralow-PGM-loading catalyst work is being curtailed.
- It would be difficult to judge to what extent this project would contribute to progress toward Program goals, since this is an incubator project. As of now, the prospects are on the positive side.
- Alignment with Multi-Year Research, Development, and Demonstration Plan goals is poor. The technology requires DME production from hydrogen, and the performance would have to exceed that of PEMFCs at reduced cost. However, the PGM loading and operating temperature characteristics are not ideal.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The project is doing well in addressing the issues the team has identified, such as establishing designs of experiment for improving both the catalyst and membrane and for developing and improving short-term behavior, and finding marketing partners. It is time to screen temporal durability.
- In the last year of this project, not too much remains to be done, except to scale to 50 cm^2 MEAs and to demonstrate projected power. That seems logical and appropriate.
- The proposed plans are largely built on past progress and appear logical. However, some of the critical indicators of the membranes are yet to be validated under the fuel cell operating conditions. It is suggested that more fuel cell testing be performed to confirm the long-term stability and performance of the membranes under practical operating conditions (e.g., subject to large current flow at high temperatures).
- The proposed work covers the incomplete milestones, 5, 6, and 7. However, the team did not propose milestone 8, which is to prove that the performance of a direct DME fuel cell high-temperature MEA is higher than that of a DMFC (slide 3). The team also did not mention measuring the "degradation rate" and "start–stop mediated performance loss." It seems that the team is running short of funding and cannot conduct these tasks.
- The project has little time left. Plans address the appropriate issues but are short on some specifics (for example, types of additives that increase DME solubility in phosphoric acid) and on how catalyst activity will be improved.
- A bulk of the work, such as scale-up and GDL optimization, is packed into the last few milestones. It is not clear what the pathway to achieving that is or what steps the project will take.

Project strengths:

- The project team is well assembled, and the investigators have demonstrated the proof of concept for effective utilization of DME fuel cells at high temperatures. The approach is well justified by the outcome of this project, and the PI clearly presented the benefits for this type of fuel cell.
- Achieving a fuel cell with an anode operating directly on an organic fuel with no reformer requires innovation. Since DME is like diesel fuel, this is very attractive, since DME is or can be a logistics fuel.

- The team consists of well-qualified investigators and scientists. The team also has access to top-class research facilities for conducting the proposed work.
- The development of high-temperature PEMs is important to the next generation of high-performance fuel cells. The proposed new membranes seem to be interesting, with some good progress being made. However, additional efforts are needed to demonstrate the anticipated benefits of the proposed membranes in actual fuel cells under practical operating conditions.
- The project is unique in that it is a commercial MEA manufacturer looking at direct DME fuel cells.
- The product exceeds MeOH performance.

Project weaknesses:

- There has been a lack of temporal screening to this point. This screening is important, as this DME technology is an alternative to DMFCs, and temporal stability has been the Achilles' heel of DMFCs.
- The overall relevance to the Program focus is low. The catalysts being studied have not demonstrated the expected advantages over commercial catalysts.
- There is no work on stability, PGM loading is very high, and GDL work was left to the last minute.
- The use of a phosphoric-acid-doped PBI membrane for a direct-water-solution-fed fuel system is a weakness. Much past research has demonstrated the instability of such acid-doped polymeric membranes, even under cathode water vapor condensation. Why the team selected such a membrane is unclear.
- Key performance indicators (including long-term stability) have yet to be demonstrated, especially under fuel cell operating conditions.
- Not much weight is placed on durability, which was mentioned as one of the main barriers.

Recommendations for additions/deletions to project scope:

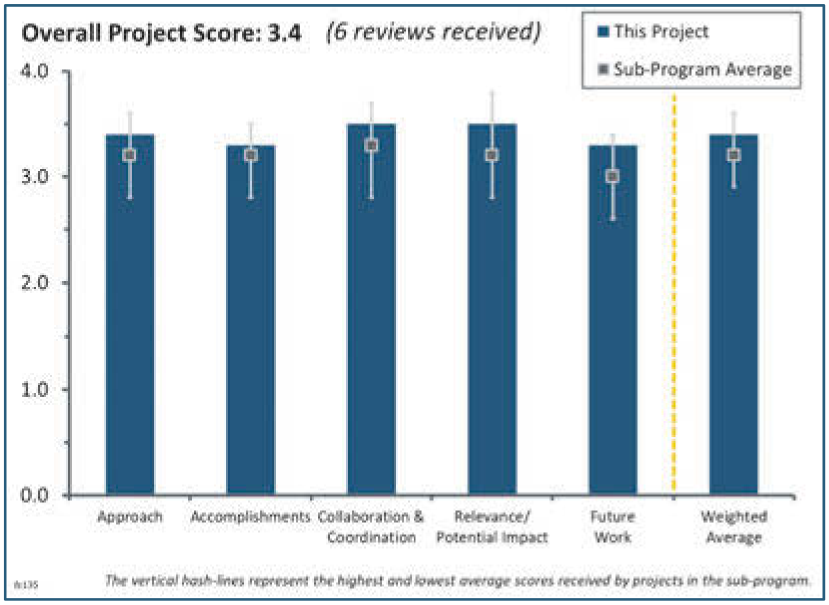
- There are three suggested additions: (1) expand to include other LANL membranes, such as the ones developed by Yu Seung Kim, if LANL and Advent corporate agrees; (2) conduct temporal screening of membrane conductivity at lower and upper temperature limits using EIS; and (3) determine catalyst stability over time at optimal fixed load (cell voltage) using chronoamperometry.
- The project is ending in December 2018. The team does not have much time to work on any proposed addition or deletion in the project. However, if possible, the team should evaluate a direct DME vapor (pressurized 30 psig) -fed system using the ternary catalyst in combination with the acid-doped PBI membrane under high temperature (240°C). The resulting data will help the team determine whether the ternary catalyst (Pt-Ru-Pd) performs better than the binary (Pt-Ru) under high pressure and temperature.
- A drastic loading reduction is needed, on par with PEMFC loading targets. Perhaps accelerated stress testing should be considered.
- Closer collaboration with the national laboratory partner is needed to perform further evaluation of membranes under practical fuel cell conditions.
- Durability should be added in the final report.
- There are no recommendations for additions or deletion to scope. The project is almost complete.

Project #FC-135: Fuel Cell Consortium for Performance and Durability

Rod Borup; Los Alamos National Laboratory

Brief Summary of Project:

The Fuel Cell Consortium for Performance and Durability (FC-PAD) coordinates activities related to the denoted development areas and supports industrial and academic developers. This effort aims to advance performance and durability of polymer electrolyte membrane fuel cells (PEMFCs). Researchers will develop the knowledge base and optimize structures for more durable and high-performance PEMFC components; improve high-current-density performance at low Pt loadings; improve component durability; and develop new diagnostics, characterization tools, and models.



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach of coordinating the investigation of the performance and durability of fuel cells through a consortium composed of the best available experts of national laboratories in a five-year project is excellent. The addition of complementary projects with other industry and academic partners completes this approach in a very efficient way.
- The project addresses critical barriers (catalysts, electrodes, and durability) that currently inhibit fuel cells from commercialization. The provided results regarding catalyst degradation, carbon corrosion, and losses due to deficits in the electrode structure are very insightful and help with understanding how to optimize the electrode structure in order to reduce platinum-group-metal (PGM) usage as well as improve durability.
- The FC-PAD approach appears to be working well. The project team is conducting significant and valuable work. The overall approach is at the correct level: pre-competitive understanding, with thrust areas that are appropriate, well defined, and well aligned.
- This project has a very structured approach, combining the strengths and capabilities of the different national laboratories involved.
- A partnership between national laboratories and other organizations is proposed to diversify the research and bring novel ideas for consideration. Four ideas (projects) have been added since FC-PAD's inception. Additional ideas would be beneficial, considering FC-PAD's scope with five participating national laboratories. The project objectives are to develop a knowledge base to mitigate mass transport losses in the catalyst layer (increased performance and lower cost) and extend lifetime without system mitigation measures. These will be achieved with characterization techniques, testing, and modeling activities. The topics currently focus on cation migration in the membrane, platinum alloy dissolution, and carbon corrosion. Mitigation strategies include ordered array electrodes and other approaches that are not ready to be divulged. The project team does not currently prioritize fuel cell contamination, although it is mentioned. This is rather surprising, considering the cost associated with system redesigns if contamination testing is delayed until an application reaches a higher technology readiness level (TRL). Also, problems are expected with ongoing vehicle deployments, especially because a number of issues are still poorly understood, including the use of cleansers to clean parts, low-catalyst-loaded electrodes and thin

membranes (smaller sulfonate site inventory) exposed to contaminant mixtures, and absence of stack-level recovery procedures.

- The central idea behind FC-PAD and its proposed approach is something that is needed. The project proposes to accelerate the understanding and technology development necessary to address many of the remaining limitations in fuel cells. It is a good mechanism to define, consolidate, and make available the resources at national laboratories to those in industry and academia. However, at face value, it can seem like just another mechanism to funnel money to national laboratories. The project team should include more universities in the funding to help address this perception.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The work to understand degradation is good. While the comparison of low-surface-area carbon and high-surface-area carbon does not show any surprises, the PtCo vs. Pt work is interesting and useful and will lead to increased understanding. It is important to link the results to modeling. The vertically aligned and porous Pt nanowire work was interesting, but the justification and feasibility for the work was not fully explained. The full characterization of the Toyota Mirai structures is very valuable, and this type of work should be continued when possible. Combining the field testing results with the accelerated stress test (AST) results was particularly effective. The modeling approach and results continue to make good progress and are focused in important areas. The effect of heterogeneities is critical and useful. The comparison of the differential cell to the modeling results and understanding differences to integral cell results are useful. The project is starting to correlate a model system for thin films with observed behavior in situ. Studying the solvent effects on inks is valuable. Understanding the inherent pH of the Nafion and how this affects the ink should lead to increased understanding and improved ability to process inks. The conditioning work is important and useful and is starting to reveal some important effects between catalyst types.
- The project team has demonstrated an in-depth analysis of membrane electrode assembly (MEA) component performance and durability aspects. A detailed understanding of the fundamental phenomena will be key to guiding future developments.
- The project team studied platinum, platinum alloy, and carbon degradation and revealed an increase in the local transport resistance. It would be relevant to return the ionomer and membrane to its original proton form to assess the relative role of the Co on ionomer conductivity and oxygen permeability in comparison to the increase in catalyst nanoparticle size. In addition, the team obtained impedance spectra with air and 21% oxygen and 79% helium for that series of tests. It would have been more informative to also obtain data with oxygen to isolate the ionomer transport contribution. Finally, it was observed that at the beginning of life, the mass transport limitations are larger for the alloy catalyst than for platinum. This observation could be the result of a smaller platinum active area (similar in effect to a lower platinum loading with Co covering Pt active sites). This hypothesis is consistent with the presented electrochemical surface areas for the different catalysts. Mathematical modeling was used to analyze several topics including oxygen transport in thin ionomer films and catalyst layers, liquid water transport in gas diffusion layers (GDLs), and cell (integral) performance. However, it is unclear if the flooding of the catalyst layer was observed to provide relevant parameter values for the model (there is apparently no direct evidence of liquid water, either as a film or as distributed droplets). A similar observation applies to liquid water transport in the microporous layer cracks. These observations are consistent with cell model discrepancies for a high value of the relative humidity. The project team designed, built, and tested two new catalyst layer structures. However, the mechanical integrity must still be improved to clearly show the potential benefits. There is a significant amount of risk associated with the proposed structures. Toyota Mirai components were characterized to provide a comparative benchmark. Additionally, the project team assessed the impact of conditioning on initial performance for several catalysts which demonstrated its importance. The characterization was limited to the catalyst and carbon support. It is recommended that the project consider ionomer characterization as well because changes are also expected considering, for example, the relatively larger sulfonate group mobility. The transport resistance measurements appear to confirm this hypothesis. The project team investigated the effects of the catalyst ink composition and processing. Also, the team studied the transport of cations within a cell and thin films, either originating from platinum alloy corrosion

or added to the ionomer and/or membrane to scavenge hydrogen peroxide and radicals. It would be more appropriate to investigate ionomer thin films on more relevant materials such as platinum and glassy carbon rather than gold and silicon/silicon dioxide, especially because substrate effects were observed.
- The accomplishments of FC-PAD have been satisfactory to this point. The greatest impact has been with regard to the development of the complex models using input from industry and academia. The development of a detailed model that can be made accessible to the general scientific public at large and can easily be tuned to fit a broad range of systems would be a great step forward. There has been significant progress made in the analysis of materials, specifically the Toyota Mirai components. However, there should not be too many resources devoted to reverse engineering.
- The project's accomplishments and progress are effective. The project clearly addresses the DOE targets in terms of performance and durability of MEAs and their components. The high number of results is reflected in the numerous publications and presentations and the quality of the different awards received. However, as there are so many results, they need to be well structured within a one-hour presentation in order not to be flooded. Therefore, the presented results should refer explicitly to the associated "Progress Measures, Milestones, and Deliverables." This year focused on PtCo alloy catalyst degradation and the carbon corrosion. The team presented interesting results on ordered array electrodes, but more details on the structures and their properties would have been appreciated. Some durability testing is missing. The second main focus was on the characterization of Toyota Mirai MEAs after 300 hours and 3,000 hours. The presented results are very informative for the community, with some unique structures (big Pt particles, F-enriched layer between catalyst layer and membrane). The project team did not mention any degradation between both MEAs, indicating that Toyota's mitigation strategies are very effective (but no pictures after 3,000 hours have been presented). However, the porosity between 29BC and after 300 hours has evolved, but the project team provided no explanation. It was unclear why the evolution of the hydrophoby of the GDL has not been investigated. Applying current AST protocols on the 300-hour-tested MEA leads instead to severe degradations. This leads to questioning whether the only reason this is done is system strategy management, as claimed. Indeed, it might be interesting to investigate the impact of the MEA structure not only in investigated AST protocols but also in automotive drive cycles. This also raises a question about the relevance of the existing AST protocols and whether they are still adapted to current MEAs or whether some should be updated.
- The project team did not generate many useful insights regarding carbon corrosion, catalyst stability, electrode structure, impact of preparation methods, or conditioning on performance. Modeling efforts support the understanding of fundamentals, as well as observed data. However, the project lacks an explanation as to how those findings contribute to overcoming the outlined barriers.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- Regular meetings occur between the five national laboratories and the four awardees (3M, General Motors, United Technologies Research Center, and Vanderbilt University). FC-PAD also has interactions with 20 other organizations (materials suppliers and institutions with specific characterization methods and mathematical modeling capabilities) and receives input from the U.S. DRIVE Partnership and other advisory panels.
- The project coordination approach is very structured for a large project that involves multiple research partners. The collaboration with many additional partners from academia and industry further enhances the consortium's capabilities and supports dissemination of the results.
- The work is well coordinated and cohesive with good communication between groups. FC-PAD is also supporting the funding opportunity announcement (FOA) projects.
- Many of the most renowned institutions, from both academia and industry, contribute to the project. The efforts and collaboration between institutions are well orchestrated.
- The collaboration between the different partners is well structured, well managed, and very efficient.
- Collaboration within and across the national laboratories within this consortium is adequate. The inclusion of industry and academia is limited to the four funded projects. The project team should develop a mechanism to make these resources more accessible and to include more collaboration with academic partners, through more FOAs or some other process.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Durability and performance are the most critical technology areas in which to continue to improve understanding. The linkages of durability with performance are intrinsic to the overall MEA structures and mechanisms being studied, and are absolutely essential to further elucidate driven-down costs. The focus on PGM-catalyst-based MEAs is also the appropriate focus, but projects that focus on catalysts alone are necessary but not sufficient. PGM catalysts at the target loadings under study will be the technology focus for many years to come. It should also be noted that the structures being studied under FC-PAD are not yet commercial and are at low TRL levels, as appropriate for this type of research. When the questions that they are investigating have been answered, and mitigations developed, industry will then—and only then—have the capability to implement results into cost-competitive products. The work that is being done is effective and, for the most part, are the most impactful activities that could be selected at the appropriate level of pre-competitiveness while making effective use of FC-PAD skill sets and considerable facilities. The work is very useful and critical to supporting industry in efforts to reduce costs to make fuel cells truly competitive.
- FC-PAD, as is true of the other existing consortia, is crucial for the Fuel Cell Technologies Office and represents a very high potential to significantly advance DOE in achieving Multi-Year Research, Development, and Demonstration Plan targets. The main targets are improving fuel cell durability and performance while decreasing the cost through a better understanding of the mechanisms involved, leading to a better mitigation solution. The high number of publications and presentations allows a very good diffusion of the knowledge learned to the fuel cell community. This kind of project fits very well with DOE's evolution toward lower TRLs.
- Understanding the basic fundamentals regarding MEA component performance and durability is very important to enable further component optimization to achieve DOE targets.
- The problems being addressed and the proposed approaches are very relevant to the key limitations of fuel cells. If more input from academic and industrial partners is included, the potential impact and pace of addressing these goals could be increased.
- FC-PAD is focused on two (performance and durability) of the three Hydrogen and Fuel Cells Program objectives (cost being the third objective).
- In-depth understanding of the interactions on a nanoscale is being developed, which is necessary in overcoming the fundamental barriers. However, it is not made clear how the single efforts and findings can contribute to optimizing performance or durability.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work is well planned and appropriate. It is important to continue to investigate different models for the ionomer thin film and local oxygen transport mechanisms. The project team should include further justification of the arrays and nanowire work, with clear go/no-go decision points on that work. FC-PAD should continue to work on material sets as it has planned, despite the fact that system mitigation solutions are available. System mitigations result in higher costs to the overall product, and improved materials are essential to bring costs down.
- The future work is very detailed, and it is clear how the project team proposes to address the indicated problems.
- The proposed future work is reasonable to further develop the understanding of the fundamental phenomena. The testing of state-of-the-art components that has been presented for components of the Toyota Mirai should be continued to develop a benchmarking standard for MEA components. This, of course, depends on the availability of state-of-the-art materials and whether it is possible to publish the results.

- The future work activities proposed are relevant and appropriate. However, the project team should propose better-quantified milestones. Regarding the results obtained from the Mirai's MEA analysis, the questions raised on the singularities observed, and the relevance of catalyst AST, the investigation should continue next year and even be extended to other "real-life" aged MEAs.
- The future work proposals address important aspects in further understanding the mechanics of the cathode. However, the work packages seem rather unspecific.
- For ionomer thin films, it would be more beneficial to use a platinum substrate instead of carbon, considering the relatively more important oxygen mass transfer resistance in comparison to the ionomer proton resistance. For water management, the project team mentions water visualization in various components. It is recommended that the project initially focus activities on hypothesis confirmation (water imaging in catalyst layers, preferably at the pore size level, water transport in microporous layer cracks).

Project strengths:

- The project has a comprehensive and cohesive effort focusing on most critical areas to understand and therefore provide the ability to mitigate performance and durability shortcomings in PEM technology. The team is systematically studying well-prioritized areas. The project incorporates strong experimental characterization tools and modeling approaches. The characterization of the Mirai structures is a new area that is incredibly valuable. This is an excellent team of the highest caliber.
- The project includes efforts from all major U.S. institutes and many important companies and therefore has a broad knowledge base and access to materials, analytic capabilities, and experience. Industry partners can reflect the necessities and problems under operating conditions. The project addresses the right problems to eventually overcome the described barriers.
- The project demonstrates the development and accessibility of the top characterization equipment and processes. The project has improved insight into the issues limiting fuel cell performance and durability. The team has developed a model that encompasses all of the processes and length scales to highlight potential solutions.
- The project has collaboration between multiple laboratories and a combination of individual strengths and capabilities. There is a strong focus on publication of the results in a large number of publications. The project team has a very valuable knowledge base for the further optimization of MEA components. Developing a kind of design guideline that provides a summary of the project's findings might be considered. A high-level executive summary of the project's results would be helpful for a fast overview of the findings.
- The multiple lead investigators are of an excellent level, and the consortium is gathering the national laboratories' core competencies and the associated huge amount of equipment. The work is conducted in a structured manner, with extensive characterizations.
- The project strengths include experimental characterization and mathematical modeling capabilities; coordination between FC-PAD members, stakeholders, suppliers, and collaborators; and focus on fuel cell performance and durability.

Project weaknesses:

- There is a limited number of FOA-funded partners and a limited scope of contamination studies. The mathematical model is based on liquid water transport parameters that is not directly measured. There is a perceived fragility of the proposed ordered array catalyst layer structures and an absence of ionomer characterization for conditioning studies. Another project weakness is the substrate choice for ionomer thin film studies.
- Although it has already been discussed and addressed in previous reviews, the focus on only the MEA components limits the performance and durability results somewhat. It would be good to provide more insight in the testing hardware for the in situ tests (especially details of the test cell/flowfield) to enhance the ability to interpret the results. In the past, the flowfield design could have a very significant impact on cell performance results, even for differential cells.
- As a consequence of the large number of activities, the project lacks a clear and understandable summary of the results of the year, how the results are positioned toward the global objectives of the project, and how the results will affect further industrial developments.

- The project needs further integration of input and funded collaboration with academia and industry to show that this is not just a mechanism to funnel money to the national laboratories. The team should focus on reverse engineering.
- The individual work packages and findings should more clearly address how they contribute to optimizing electrodes and MEAs and overcoming the defined barriers.
- The slides could have better diligence on defining experimental details and materials sets to which the data refers.

Recommendations for additions/deletions to project scope:

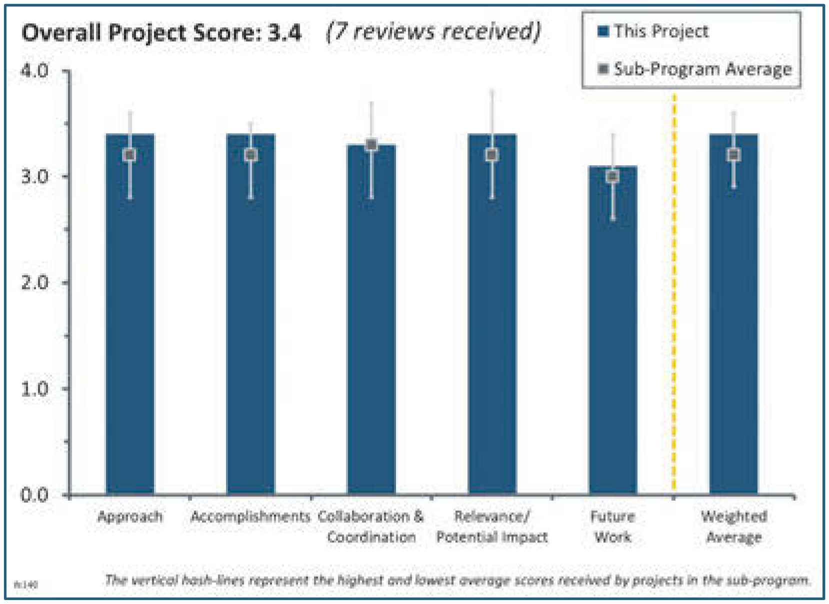
- The project team should further investigate the discrepancy between the AST protocol results and the Toyota Mirai testing results. It is true that the target of the AST protocols is to develop an understanding of fundamental phenomena on the materials side. However, special attention should be paid that the materials are not "over engineered" to achieve the best performance in the AST protocols when alternative, lower-cost approaches could meet the requirements of real-world applications. Based on the know-how gained from real-world operation of the latest vehicles, the team should develop a second set of test protocols that can be used by materials developers to optimize their materials. (As an example, there are trends where too-harsh ex situ testing conditions for coatings of metallic bipolar plates did not reflect the performance in real in situ operation.) The extension of the state-of-the-art testing to additional materials and documentation of the material's results in scatterbands would be great. Of course, this requires the "okay" from the manufacturers, but if the FC-PAD team can discuss with other original equipment manufacturers and qualify materials similar to Toyota's, that would be very helpful for the overall development. It might be worthwhile not only to address degradation phenomena but also to develop approaches for regeneration strategies, if possible. The work on activation and break-in procedures is very important. The project team should pay special attention to this because a short and efficient break-in procedure will be key for low-cost, high-volume production of automotive fuel cell stacks, where stack conditioning time is one important cost driver.
- The results could state more clearly the impact on the key performance indicators. It would be helpful if the findings could be transformed into design rules in order to facilitate optimization. A reference system (e.g., MEA, operating conditions, standard measurements) could be defined, which then could be used to demonstrate whether the findings can be translated into an optimization of performance or durability.
- The project team should improve the timelines and the quantitative description of milestones. The presentation for the review should be provided in time in order to enable the reviewers to work on it adequately before the Hydrogen and Fuel Cells Program Annual Merit Review.
- The project should incorporate more funded collaborations with industry and academia and limit the effort associated with reverse engineering of commercial materials.

Project #FC-140: Tailored High-Performance Low-Platinum-Group-Metal Alloy Cathode Catalysts

Vojislav Stamenkovic; Argonne National Laboratory

Brief Summary of Project:

A primary focus of the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (the Program) is development of highly efficient and durable Pt alloy catalysts for oxygen reduction reactions (ORRs) with low Pt content. This project will go from fundamentals to real-world materials to achieve rational design and synthesis of advanced materials with a low content of precious metals. Researchers are taking a materials-by-design approach to design, characterize, understand, synthesize/fabricate, test, and develop tailored high-performance low-Pt-alloy nanoscale catalysts.



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The proposed technology is based on the well-established materials-by-design principle, which includes design of material, characterization, evaluation of electrochemical performance, and analysis of the data. The principal investigator (PI) clearly emphasized both project objectives and existing critical barriers. Overall, the project description is easy to follow. The targets and methods of the project team's accomplishments were rationally selected according to the DOE requirements. The project integrates relevant effort and is feasible based on the progress reported.
- The overall approach is excellent, covering development, characterization, and small-scale fabrication of platinum-group-metal (PGM) ORR electrocatalysts. The development of catalysts is based on translating materials and knowledge developed on well-defined systems (single crystals and thin films) to practical nanoparticles. The inclusion of small-scale production is especially relevant, as effective catalyst design also needs to be compatible with practical fabrication methods.
    - Argonne National Lab's (ANL's) characterization is directly relevant to meeting project objectives, and the project team has many unique and unmatched capabilities. The increased focus on membrane electrode assembly (MEA)-level testing is critical for understanding limiting factors and is therefore appreciated.
    - One aspect of the approach that could use improvement is inclusion of work specifically aimed toward understanding the factors responsible for the circa 10x (or more) reduction of catalyst mass activity when translating from rotating disk electrode (RDE) to MEA. It is unclear whether ionomer adsorption is alone responsible or other factors are responsible (e.g., catalyst degradation in the MEA). The resolution of this issue would substantially increase the operating efficiency of polymer electrolyte membrane fuel cells (PEMFCs) and increase commercialization probability.
    - ANL is also continuing the development of the porous and hollow catalysts. While extraordinarily active in RDEs, the team will need to assess the characterization for activity and durability in the MEA. It is unclear whether such highly engineered structures can remain intact after MEA evaluation, including accelerated stress tests (ASTs).

- ANL has an excellent organization of efforts, with clearly defined tasks and roles for each national laboratory partner to contribute to a common objective.
    - The intent of associating catalytic function and performance with microstructures and compositions should be the best means for developing comprehensive insights into the fundamental mechanisms. Ultimately, this path should lead to solutions for maximizing the efficiency of the catalysts to reduce costs of fuel cell MEAs. It is not fully apparent in this presentation just how far this project has gone toward its initial objectives.
- The approach is excellent. The RDE-inductively coupled plasma mass spectrometry (ICP-MS) measurements of catalysts with scale-up, and real fuel cell measurements against baseline materials, provide credibility.
- ANL used conventional wet chemistry to synthesize highly dispersed Pt nanoparticles deposited onto carbon support. ANL's approach of first synthesizing Pt nanoparticles and then supporting these nanoparticles on high-surface-area carbon resulted in high Pt surface catalysts with a high electrochemical surface area.
- ANL has an excellent materials-by-design approach and very good coordination among the partners and laboratories.
- The approach is very scientific and well defined.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team successfully synthesized different monodispersed nanoparticles with uniform compositions. The team also demonstrated synthesis of Pt_3Au nanoparticles on carbon support to obtain almost zero Pt dissolution and highly stable Pt catalysts above 1.2 V.
    - ANL has demonstrated scaling up of various catalyst architectures (e.g., nanopinwheels, nanocage) without performance loss or particle agglomeration. The comparative particle size and distribution between the catalysts made through batch method and flow reactor for high-speed production is commendable (slide 19). The retention of an original monodispersed catalyst structure with a large-scale synthesis method is a great accomplishment.
    - The team also proved the versatility of their synthesis process. They have demonstrated the method with different supports and loadings capable of controlling the catalyst active surface area. This helped the team to achieve high mass activity of 500 mA/mg_{Pt} with a PtNi catalyst. The catalyst also performed almost two times better compared to the commercial catalyst from TKK.
    - The team demonstrated a PtCo intermetallic alloying method to make a catalyst with Vulcan carbon support to improve Pt and Co dissolution and achieved 700 mA/mg_{Pt} with a PtCo catalyst. Overall, the team demonstrated the flexibility of their catalyst synthesis tolls to make a monodispersed low-loading catalyst with high mass activity that has the potential to meet DOE's 2020 performance targets.
- The team of ANL, Oak Ridge National Laboratory (ORNL), and the National Renewable Energy Laboratory (NREL) achieved excellent progress in all tasks (Tasks 2–5). The PI summed up these tasks and shared them with the community.
    - The project team demonstrated the accomplishments that had been experienced on several levels (as it was originally proposed by Dr. Stamenkovic): (1) an understanding of the fundamental origin of intrinsic ORR activity of Pt and PtM catalysts, based on preferential exposure of crystallographic planes, (2) the selection of nanostructures enriched with these facets (shaped nanopinwheels), (3) the synthesis and scale-up, and (4) the comprehensive analysis (physicochemical), followed by fuel cell tests. For 1-3, either the critical barriers were addressed, or the selected pathway will unambiguously result in the successful meeting of all DOE targets, with outstanding results (the preservation of shape and connectivity in Pt-structure with batch size increased from 0.1 to 3–5 g).
    - Taking into account a completely different integration of shaped nanoparticles on non-specifically designed supports into the MEA structure, the progress in electrochemical evaluation is excellent. It demonstrates coordinated teamwork between members of this project. The electrochemical activity of the catalyst (measured at high potentials) is at least two times higher compared to commercial Pt/C catalysts, while the loading of platinum was decreased to 0.03 $mg(Pt)/cm^2$. The overall demonstrated progress excludes any doubts of how the team addressed critical barriers to achieving DOE goals (listed as milestones and go/no-go points in the project).

- The team has continued to make excellent progress meeting the project's catalyst objectives, which are well aligned with DOE goals. Along with demonstrating the high activity of new catalysts in RDEs, which exceed the DOE target by >10x, the team has made good progress in demonstrating the scale-up feasibility of several project catalysts.
    - The team has made good progress toward integration of project catalysts in MEAs. The additional focus on the integration of the catalysts into high-performance electrodes/MEAs that are capable of demonstrating performance approaching entitlement is warranted.
- This is almost the end of the project. The team developed many high-ORR active catalysts, which showed excellent results in RDEs. The team introduced the MEA tests pretty late in the project. If the project team had introduced MEA tests earlier, it could have helped in designing or modifying existing designs and composition of developed catalysts to make them work better in the MEA. The MEA data shown with very low Pt loadings (around 0.03 mg/cm^2) is very impressive.
- The project has exceptional synthesis of novel materials and scale-up.
- The scale-up and fuel cell performance is a major accomplishment of this project.
- Although extensive characterizations were performed, and testing indicates some properties were improved in the test samples, there was no clear indication of how much direct progress had been made over the past three years of effort toward MEA milestones.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- Despite having world-class expertise in designing shaped nanoparticles as well as characterizing and evaluating fuel cells, the team established several important inter- and intra-institutional collaborations that provide substantial benefits for the success of the whole project. Those collaborations included practically all national laboratories participating in the fuel cell effort, a number of small U.S.-based businesses, and, recently, the research and development centers from automobile OEMs.
- The team has good collaboration between the three national laboratories: ANL, ORNL, and NREL. ANL has extensive catalyst synthesis and characterization expertise, ORNL has extensive catalyst-coated membrane (CCM)/MEA characterization expertise, and NREL has expertise in CCM/MEA and fuel cell testing. The collaborators are all complementary to each other, and together, they have all the expertise and resources needed for carrying out the proposed tasks in this project.
- This project has excellent collaboration between ANL, ORNL, and NREL on synthesis, analysis, and MEA testing, respectively. The team should approach other laboratories, institutes, and/or industry to test the active catalyst in the MEA once the scale-up issues are sorted out.
- The level and types of collaboration are good. The collaboration is appropriate for a catalyst development project, including apparently increased collaboration on MEA-level testing and diagnostics. Additional collaboration with state-of-the-art original equipment manufacturer (OEM) catalyst and electrode developers would be useful, as OEMs could potentially increase the probability of demonstrating relevant performance in MEAs.
- This project appears to have a high level of cooperation with the group of national laboratories. It is less clear whether interactions with outside groups of OEMs were very active.
- The partners are only national laboratories; these materials need to get into the hands of fuel cell system manufacturers or MEA manufacturers. This will flush out any remaining technical challenges with these materials.
- This project needs more collaborators other than national laboratories.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The relevance of the project is outstanding. The team is directly addressing key fundamental activity, cost, and durability barriers that are critical to enabling further commercialization of PEMFCs. No other PI or catalyst research organization has the breadth of expertise and capabilities demonstrated by this project.
- The PI emphasized the relevance of the proposed technology to the DOE mission during the Program Annual Merit Review meetings. ANL has already demonstrated the impact: the critical step of scaling up highly active (but at the same time possessing high surface free energy) nanostructures to TRL 2–3 (up to 5 g), in combination with an impressive intellectual property portfolio (11 in total), resulted in OEMs' interest to the technology. The team successfully supports and advances progress toward Program goals and objectives.
- The impact to the field can be enormous. The scope of work directly addresses performance, cost, and durability targets.
- The project targets are all relevant to DOE's 2020 targets. The team has focused very carefully on achieving DOE goals and has designed the tasks accordingly.
- The potential impact of these new catalyst materials appears to be high, particularly with the major boost in fuel cell performance in the laboratory environment.
- The project does align well with DOE's hydrogen fuel cell research direction for low-PGM catalyst development. To meet DOE 2020 targets, the project team would need greater efforts to evaluate high-current-density MEA challenges of low-PGM catalysts.
- Although the project team presented numerous images of support catalysts and the tests indicating improvement of various parameters, such as voltage, the actual progress for meeting the DOE MEA targets with lower concentrations of Pt-based catalysts was not apparent. In particular, it was unclear what the expected behavior would be, based upon the "best" materials identified during the three-year course of this project. There was no evidence of any major advances having been made.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future work plan is directly relevant to addressing key fundamental barriers for PGM ORR electrocatalysts, but current funding is set to expire this year. It would be good for the work to continue, especially the resolution of the MEA integration challenge of activity loss.
- The project is coming to an end in October 2018. The future work, broadly described by the PI on slide 30, is relevant to the development of high-performing, low-PGM loaded catalysts. The team may pursue this work with future funding.
- The proposed plan on the remaining budget period is well justified and will cover the team's remaining deliverables, according to the original statement of project objectives.
- Since this project ends in October 2018, there will not be much more additional work performed, other than completing current tasks and writing the final report. The authors should thoroughly and explicitly document what was found to enhance the performance of the studied Pt-based catalysts. In particular, they should note whether these studies led to substantial reduction of the quantity of catalyst needed to yield MEAs that could achieve DOE performance levels.
- The team should include durability in operating fuel cells in the future work. Although the RDE coupled with ICP to look at Pt dissolution was novel and clever, it is not clear whether it has any correlation to real fuel cell system durability. Thus next steps should include performing an AST on MEAs made with the new catalyst materials.
- The future work should be prioritized for resolving surface chemistry in the MEA and simultaneously scaling up in grams (to at least the 5 g level) so more MEA evaluations can be done. Alternate approaches for catalyst synthesis should be lower in priority compared to alternative supports, which may result in more improvements in MEA for high-current-density performance.
- The project's future should include fuel cell testing of materials.

Project strengths:

- This has been a highly coordinated team of experienced researchers from several national laboratories utilizing specialized experimental capabilities focused on the common objective for improving performance of Pt-based catalysts. The team produced a variety of Pt-based catalysts and characterized their dimensions and composition extensively.
- The team has demonstrated new catalyst materials that show good promise of bringing down PGM costs. The scale-up and fuel cell performance data are key to demonstrating the potential of the research.
- The team has an unparalleled fundamental understanding of ORR catalysis from theory to materials fabrication and characterization. The team has a focused effort on limited scale-up.
    - Another project strength is the demonstration of catalysts with more than ten times the DOE target for mass activity.
- The input into understanding the correlations between the performance of Pt catalysts measured in RDEs versus MEAs has a substantial impact on the fuel cell community. The proof of concept in highly durable nanoparticles, as well as in well-defined Pt alloys (intermetallic systems) that can be scaled to feasible amounts, is impressive and is definitely a breakthrough in the field. The series of PtNi and PtCo with multilayered Pt shell and novel nanopinwheel structures already exceeded the DOE 2020 technical target for mass activity in MEAs.
- This project has a great team. This is a good ensemble of expertise and technical resources to work on such a complex project.
- This is an excellent team of researchers from ANL, ORNL, and NREL, with an excellent materials-by-design approach. Many high-ORR active catalysts have been developed, characterized, and tested.
- This project has made significant progress in producing a novel catalyst, as well as the ability to scale up.

Project weaknesses:

- According to the presented progress, demonstrated accomplishments, and impact on the field, programmatic weaknesses are insignificant. Several minor optimizations in the scale-up tasks that could result in higher yields (~15%) definitely should be considered as continuation of scientific discourse and cannot be considered as impeding project success.
- The project team should include more MEA evaluations at an earlier stage of the project to provide feedback to the catalyst design. The RDE is an excellent tool, but there is too much dependence on RDE data to judge the catalyst viability; this could be tricky. The project team could have prioritized the scale-up efforts with the help of a catalyst supplier's feedback.
- The primary project weakness is that electrode optimization efforts are likely not sufficient to achieve entitlement performance with these high-activity catalysts. Additionally, the project needs more characterization of catalyst composition and structure after MEA testing to assess degradation modes.
- No summary evidence was provided that demonstrated any significant improvements in reducing Pt contents while meeting or achieving the performance targets for subsequent MEA devices resulting from this project. While several electron microscope images of embedded Pt clusters were presented, the correlation to reaching the performance levels was not shown.
- The project was heavy on catalyst design, synthesis, and electrochemical characterization, but it did not have much on in situ fuel cell characterization or any fuel-cell-system-level characterization.
- The project is missing fuel cell durability data and collaboration with industry.
- The project needs industry input.

Recommendations for additions/deletions to project scope:

- Since this task is ending within a few months, there is no need to alter project scope. However, the team should clearly identify what processing steps led to improved behavior from the catalysts. The team should also fully document all issues and approaches that did not succeed.
- The project should be extended to enable additional ORR catalyst development with specific focus on determining and resolving the mechanisms for deactivation in MEA electrodes as compared to RDEs.
- The project's remaining timeframe does not allow time to propose additional sub-tasks to the project scope; however, the proposed future activity is well designed and balanced.

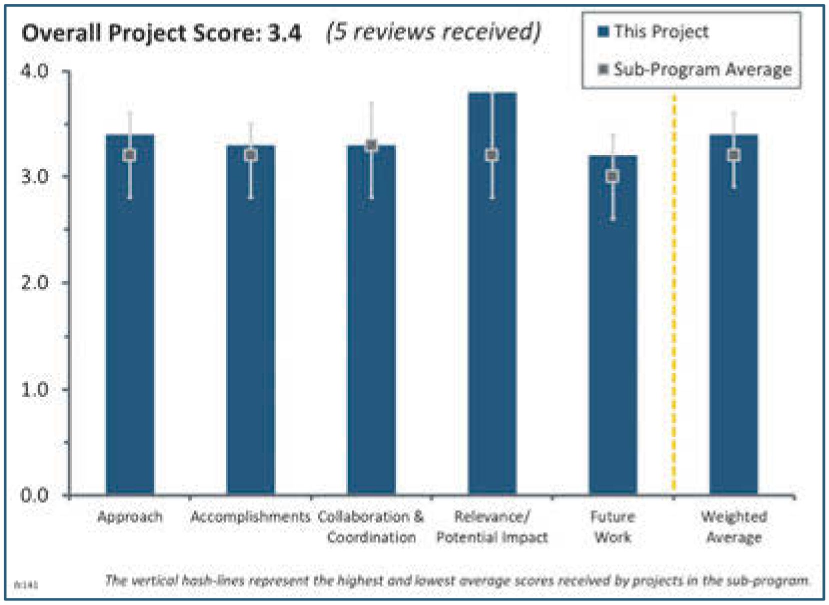
- The project is successfully ending soon. If there is any next phase, then more scale-up and MEA tests to meet high-current-density targets would be great. The team has already met loading targets.
- The team should focus more on collaboration with industry; however, the project is ending in four months.
- The project should be continued.

Project #FC-141: Platinum Monolayer Electrocatalysts

Jia Wang; Brookhaven National Laboratory

Brief Summary of Project:

This project aims to synthesize high-performance platinum monolayer electrocatalysts for the oxygen reduction reaction consisting of a platinum monolayer shell on stable, inexpensive metal, alloy, metal oxide, nitride, or carbide nanoparticle cores. Three low-platinum catalysts will be developed that will meet the U.S. Department of Energy technical targets for 2020.



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project focuses on improving catalyst durability and performance by using advanced core–shell nanostructures with various synthesis and processing methods.
- The approach in this project was well placed, which is justified by the outcome.
- The catalyst synthesis strategies and compositions that the project team are developing are interesting considering the excellent rotating disk electrode (RDE) results. However, the project team should put more effort into fundamentally understanding why the mass activity is so much lower in the membrane electrode assembly (MEA) tests versus RDEs.
- This project started with a very broad approach to core–shell catalyst design and has converged on a few approaches. The range of topics is still quite diverse, but the project has made intriguing discoveries that may merit more focused study. For example, it is argued that the Pt/NbO catalysts have a specific morphology, but evidence for this morphology is lacking.
- The approach targets the most critical aspects of platinum-group-metal (PGM) catalysts (high electrochemical surface area (ECSA), reduced PGM content, and scale-up to MEA-relevant quantities). However, it is clear that further MEA design was warranted in the project, as MEA ECSA was vastly inferior to RDE results, the 0.2 mg/cm^2 baseline showed oddly poor performance, and the MEA data were poorly interpreted.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has shown excellent RDE results with several varieties of catalysts and promising initial results in MEAs at low current density. Considering electrode optimization was not the focus of the project, the catalyst-specific results were very good.
- The principal investigators achieved significant progress in this project by introducing a number of highly diverse systems. Electrochemical evaluations in RDEs showed great performance, and promising catalysts were synthesized to multiple gram amounts. In addition, the team performed an MEA test to address DOE technical targets. Despite very promising RDE evaluations, it is apparent that catalyst performance in the MEA was not at the expected level, and the DOE target for mass activity was not achieved.

- The team carried out investigations on five electrocatalyst designs, and the results were clearly stated. The performance results by RDE were supported by MEA testing for selected structures.
- The project has delivered proof-of-concept studies with performance data and some scale-up on a range of catalyst designs.
- At the RDE level, only the PtNiN/C catalyst appears promising. The other catalysts all have either low mass activity or low ECSA. Also, the summary table on slide 15 does not include ECSA. This is odd, as General Motors (GM) is a partner on this project and has been a strong proponent of the importance of ECSA for any catalyst targeting PGM loadings of ≤ 0.1 mg/cm^2.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The collaboration with the participants in this project was coordinated in an excellent manner.
- Good collaboration appears to exist between the partners, industry, and academia, and the studies are coordinated well. However, the contributions from partners are not always explicitly stated.
- At the catalyst level, the project showed strong collaboration. However, it looks like only limited collaboration was achieved with MEA integrators. As MEA integration is such a critical aspect of this project, the project probably warrants more involvement from GM/Toyota.
- There seemed to be appropriate partner organizations on the project. It was difficult to determine whether all of the collaborators contributed significantly based on how the data were presented. It seems that stronger collaboration on MEA synthesis would be beneficial, as it was not clear how much effort MEA partners put into optimizing MEA preparation.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project was highly relevant to DOE's PGM targets, and further investment in this line of work is strongly recommended.
- The project points the way for a number of catalyst concepts, including the potential for scale-up. Industrial partnership increases the potential impact.
- The project scope and goals align well with DOE objectives on catalyst performance and durability for fuel cells.
- The project is advancing the development of novel catalyst compositions that show promise for addressing key catalyst technology challenges.
- This project is one of a few that has very high impact on the DOE Hydrogen and Fuel Cells Program (the Program).

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- This is the last year of funding for this project, and proposed future work is reasonable for the amount of time left.
- Future work tasks, such as MEA testing/optimization and scale-up, are key to achieving the project objectives.
- The catalysts appear to have intrinsic activity, so it is not necessary to further improve activity. The focus should now move to MEA testing/optimization.
- The proposed work follows logically from current accomplishments. The final studies of this project should focus solely on MEA-scale performance and durability. The proposed PGM-free work is intriguing but not within the scope of this project.

- The project should move forward with the proposed work on core–shell catalysts; the team should not switch the focus to PGM-free catalysts. This group has already made great progress with PGM catalysts (particularly the PtNiN/C catalyst). The team should stick to its strengths. While promising, much of the PGM work shown at this Program Annual Merit Review (including the current project) is at a very low technology readiness level (2–3). Thus, it is too early for industry to get involved, and further funding is necessary to advance this critical work.

Project strengths:

- The project can be viewed as one of the most valuable efforts funded by DOE and the Fuel Cell Technologies Office. The outcome from this effort is a long list of highly diverse Pt-based systems that can be readily applied to the MEA. The main value from this effort is correlation between fundamental properties and functional behavior of catalytically active systems.
- Brookhaven National Laboratory is continuing to produce exciting, next-generation core–shell catalysts that will likely be a core technology in the coming years. The goals of this project are fully aligned with some of the key current bottlenecks to polymer electrolyte membrane fuel cell commercialization.
- This project has good partnerships with industry, the national laboratories, and academia. The results and progress are summarized well, and the team has made good progress toward scale-up and MEA testing. The team has produced a good set of publications.
- This is, thus far, a fruitful project that has led to important discoveries of techniques for core–shell catalyst design, manufacture, performance, and durability. The Co nanowire morphology and NbO_x approaches are particularly intriguing. The results provide a strong platform for future detailed study.
- The project is developing interesting catalyst compositions with promising intrinsic activity and durability.

Project weaknesses:

- The broad range of studies presented limits the ability of this project to go into detail. In particular, a more detailed discussion of the Pt/NbO morphology would be of interest.
- The MEA integration activities were disappointing. More work needs to be performed here to understand where the large discrepancy in ECSA originates. Also, ECSA should be included in any future summary catalyst, as this is a critical parameter for high-current-density operation.
- The activity and performance results are not transferring to MEA testing.
- This effort has not yet delivered a high-performing catalyst that can achieve or exceed DOE technical targets simultaneously.

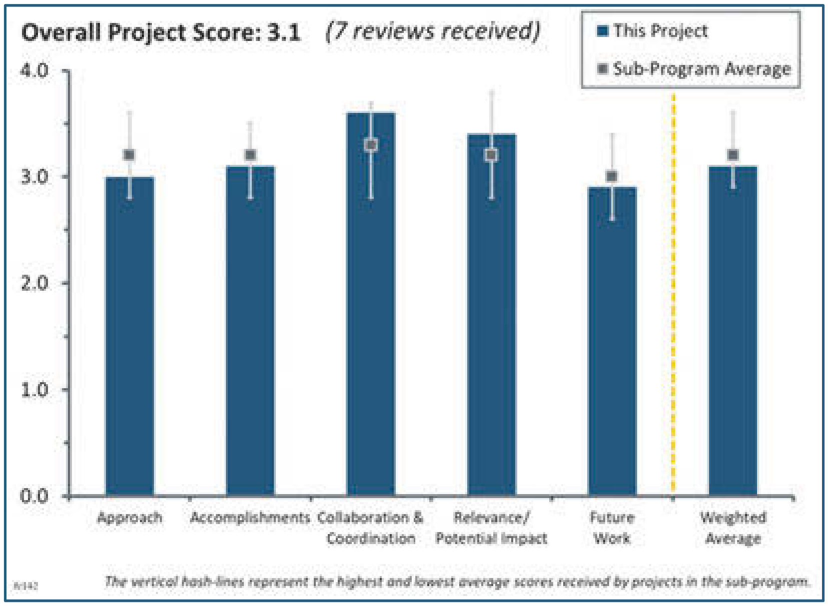
Recommendations for additions/deletions to project scope:

- The project team needs to continue toward simultaneous improvement in durability and activity of promising structures supported by scaling up and MEA optimization.
- The project should not focus on improving intrinsic activity and/or RDE testing any more. Instead, the focus should be on improving MEA results or understanding why the results do not match the state-of-the-art results at the MEA collaborators (GM and Los Alamos National Laboratory).
- For the remaining time in this project, the researchers should focus on effective transfer from RDEs into MEAs.
- The project team should focus on PGM catalysts. It is disappointing to see this team switching focus to PGM-free catalysts.

Project #FC-142: Extended Surface Electrocatalyst Development

Bryan Pivovar; National Renewable Energy Laboratory

Brief Summary of Project:



Platinum catalysis remains a primary limitation for fuel cell commercialization. This project is developing durable, high-mass-activity, extended-surface platinum-based catalysts for decreased fuel cell cost, improved performance, and increased durability. Researchers are focusing on novel extended thin-film electrocatalyst structures (ETFECSs), a particularly promising approach. Parallel efforts include novel extended nanotemplates; atomic layer deposition (ALD) synthesis of platinum–nickel nanowires; and membrane electrode assembly (MEA) optimization and testing including multiple architectures, compositions, and operating conditions.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- Using ALD of Pt on Ni and Co nanowire (NW) to make an alloyed low-loading catalyst is a good approach to making stable catalysts. The team has demonstrated their approach on a small scale successfully and is getting good results in large-scale production with ALD. This approach is expected to give a durable catalyst, as the support material is solid NW, which is not prone to degradation as carbon support material.
- Extended surfaces can address many of the limitations of nanostructured Pt catalysts, namely specific activity and durability. The key to the approach is the demonstrated ability to scale the ALD process, potentially to the kilogram scale. The progression of the project to this point and the proposed future work are well aligned to address many of the remaining issues and questions.
- The project has excellent focus on key barriers, including mass-transport limitations at rated power, scale-up, and durability. One durability measure has been met, and the project is close to a second. A pathway to scaled-up and improved rated-power performance is described, but the route to improved durability is not yet clear.
- The work is laid out, and key barriers are identified.
- The overall approach is satisfactory and has resulted in the generation of high-mass-activity catalysts in the rotating disk electrode (RDE). However, it remains to be determined and demonstrated that the overall approach will result in active, high-performance fuel cell MEA catalysts. One primary challenge is that it is unclear whether the ETFECS structure with the hollow core (after dealloying) will be stable against electrochemical cycling, which does not appear to have been assessed to any significant extent (it is mentioned only on slide 24). Another aspect of concern is that there appears to be relatively little MEA testing with exposure to hydrogen/air with state-of-the-art components (e.g., thin polymer electrolyte membrane [PEMs]); this testing process is critical for assessing impacts of residual transition metals. There is also little characterization of structure and composition evolution after fuel cell testing and durability testing.

- The approach has been improved from past years since durability and high-current performance are receiving greater emphasis in the recent milestones. However, electrocatalyst cycle durability would be more valuable to observe than durability to the support corrosion accelerated stress test (AST). The electrocatalyst cycle should have received higher priority. The analysis of durability and mass-transport resistances has been enabled by the removal of excess Ni in the catalyst concept presented last year. The ability of ALD NanoSolutions, Inc. (ALDN) to produce three tons/day was noted by the presenters in the question-and-answer session. It is good to see an approach based upon a catalyst that can be scaled. The project is now over two years old, and there have been opportunities to revise milestones, so it appears late to be addressing robustness, electrocatalyst cycle stress testing, and power densities that extend beyond 600 mW/cm^2. These matters should have been addressed earlier.
- The approach for this project is aimed at developing durable, high-mass-activity, extended-surface Pt catalysts, and optimizing MEA performance and durability for these materials. Two major issues remain. First, the team needs to come up with a verified process, such as the acid-leaching step, to make the MEA fabrication process viable. It is well known in the PEM technical community that any leftover Ni in the electrode will quickly destroy the membrane, significantly decrease cell performance, and affect durability. This project does not define a method for verifying that Ni does not and will not leach out of this catalyst. Second, the mass activity is low, and there is a very large variation from batch to batch. Project modifications need to address process control.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Roughly 70% into the project, the team has demonstrated good progress, meeting performance and batch processing milestones. The researchers have developed methodologies to gain better control of the Ni content in the thin film and have identified more optimal processing and post-processing handling methods to improve activity metrics. The project team has also met the DOE durability target, which has been questioned in the past.
- The team has done well since the 2017 DOE Hydrogen and Fuel Cells Program Annual Merit Review (AMR). First, the team has demonstrated catalyst mass activity of >440 mA/mgPt, meeting the DOE target for 2020. Second, the project team has synthesized a large-scale (>5g) catalyst with a high mass activity of >500 mA/mgPt. Third, the acid-leaching step seems to be crucial for obtaining well-performing catalysts; the team has a good handle on this process and has demonstrated batch reproducibility of this step. Fourth, the project team has developed an ALD method for binary catalysts Pt and Ni on Co NW and hence has controlled the amount of Ni in the catalyst well. Finally, the team has demonstrated 5,000 hours of durability, meeting DOE's target of less than 40% performance loss. Overall, the team has accomplished some of the important DOE goals. However, the goal for electrocatalyst durability was not met. The team should investigate whether the loss of mass activity is due to the loss of Pt from the NW surface. Pt loss and its inherent integrity on the NW have not been considered or analyzed by the team.
- The project group understands the pros and cons (e.g., too much transition metal is bad). Mitigation and development is steady. There is a minor issue: progress is confounded by providing polarization curves in A/mgPt. Industry identifies 900 mV for mass activity (for which the team provides data). Polarization curves can be added with current density (A/cm^2) on the horizontal axis. If the team wants to provide H_2/O_2 polarization curves, that is fine.
- Good progress has been made toward demonstrating mass activity, which exceeds the DOE target in MEA, perhaps owing to optimization of oxygen concentration during ALD. Some electrode optimization work has been conducted, showing potentially improved hydrogen/air performance on slide 16. However, the performance still remains quite low relative to state-of-the-art MEAs, and it is unclear whether the underlying factors for the lower performance are understood. Electrocatalyst durability is a key parameter and needs to be significantly improved.
- For 0.1 mgPt/cm^2 cathode loading, hydrogen/air polarization was improved to approximately 0.8 A/cm^2 at 0.6 V (fully humidified, 80°C, 150 kPa). This is still far shy of the 2020 power density target (1 W/cm^2) but does represent progress from the year before. The use of a PtNi to C optimization was a good measure for the project to take to understand how to make the most of the catalyst. Low-temperature performance and

robustness testing is yet to be reported. Electrocatalyst cycle durability needs to be reported. Good mass activities have been consistently shown from various batches with scaled-up catalysts. In general, the project has done well to pay attention to the manufacturing scale possible for the catalyst.

- The project has met all of its milestones thus far.
- Performance is still low. There has been significant progress at the RDE level, but there is a long way to go, and the performance at the MEA level is not nearly as good. In addition, performance variations are very high for both types of testing, suggesting that significant additional efforts on optimization of both the catalyst and the catalyst layer will be required. The authors claim that the "local mass transport is not limiting"; however, the data suggests significant mass transport issues when operating in air.

Question 3: Collaboration and coordination

This project was rated **3.6** for its collaboration and coordination with other institutions.

- Key personnel are fully qualified, as demonstrated by the successful completion of previous projects and by the team's publications on work in this and related fields. The proposal clearly and completely defines the roles and contributions of each team member, including financial support from partners. The final team, facilities, and equipment required to complete this project are fully in place, ready, and available. This project has full commitment from the partners' senior management and corporate officers. Ample facilities are available to support and complete the proposed work.
- The team is composed of well-known technical personnel from reputed academia and national labs. ALDN has demonstrated the capability of making ALD catalysts on a large scale. Overall, the task coordination and information/data flow between the collaborators is happening well. The principal investigator is very capable of coordinating tasks between multiple collaborators.
- The fact that the project delivered a no-go decision on a partner whose task did not work out is a positive for the project. More projects should cut tasks in a like manner. The collaboration with ALDN has been particularly effective in answering questions about scaling up the catalyst concept. While it would be a waste of taxpayer funding to fully optimize and engineer scaled-up batches of catalyst within a specified degree of repeatability, the project has done more than enough to alleviate concerns regarding manufacturing scale. Other national laboratory projects have not done nearly as well in representing manufacturing scale. CSM appears to have delivered high-resolution elemental maps of where Pt, Ni, and Co exist in the NW. The project slides could do better in confirming CSM's contributions. CU appears to have discovered preferred ALD routes with 5% O_2 and co-deposition of Pt and Ni. The slides would benefit from making the CU contribution clearer.
- Both the imaging and elemental analysis were good and clearly help the project. The local transport work is good.
- Collaboration, organization, and feedback have been effectively designed and utilized.
- The project team, including Colorado University (CU), Colorado School of Mines (CSM), and ALDN, coordinated well together.
- Collaboration appears to be appropriate, but it is not perfectly clear which organizations contributed on each slide. It may help to list, on individual slides, organizations that made direct contributions to the results.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- As in the past, the relevance of the project is strong because of the role catalysts play in overcoming the cost and durability barriers to fuel cell commercialization. This is enhanced by the fact that the project is working on a low-platinum-metal-group (low-PGM) catalyst, which has a considerably shorter road to commercialization than a PGM-free catalyst. The one valid basis for questioning the project relevance would be if the project had no intent of addressing high-current-density (HCD) performance. Developing a catalyst just for the sake of high mass activity could actually be irrelevant, especially given the efforts by developers not to have stacks ever operate at 0.9 V cell potentials (for the sake of durability). However, the project has clearly shown polarizations measured under hydrogen/air at higher current densities. Although desired performance has not yet been achieved, progress has been made toward higher power density, and the project is targeting higher power density.

- The project is relevant to DOE's 2020 target of achieving 0.125 g/kW combined PGM content in both electrodes. The new approach of making high-performing catalysts using the ALD method to achieve catalysts with high mass activity and possibly durability is expected to make a great impact on DOE's overall mandate to commercialize FCEVs.
- Extended surfaces address many of the limitations associated with nanoparticulate-based materials, giving this project a high level of potential significance.
- This project represents a potentially effective approach to manufacturing low-loading electrocatalysts.
- New catalyst work is important. It is important to evaluate structural changes for potential significant improvements. However, the massive size and hollow nature of the wires is of concern for meeting metal area and loading targets.
- The project is directly relevant to the DOE catalyst targets. However, it is unclear whether the performance, electrocatalyst durability, and activity challenges in MEAs are resolvable over the remainder of the project term.
- Reducing PMG loading is critically important to the successful commercialization of PEM fuel cells. The potential for this conceptual approach to be successful has not been demonstrated.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- Key issues are addressed, and the team is there to do it.
- On slide 19, the team has identified and listed the remaining challenges in the project and proposed them as future work. The "post-processing optimization" and "minimization of mass activity/[electrochemical surface area] of the catalyst" are two of the most important actions, which the team has acknowledged. The team's planned future work is aligned with the project's remaining challenges. The team could have included some durability cycle studies (e.g., load/humidity cycling and start/stop cycling) to get vital information about the ALD-made catalyst durability under automotive operational condition.
- The proposed future work is good. More detail is needed in terms of the electrode optimization to decrease transport losses. A strategy to move beyond carbon additives for improved HCD performance would be ideal.
- Approaches to performance issues are clearly defined; however, mitigation of durability issues could be improved.
- Optimization of ALD batches is discussed in the future work, but the priority for optimization is missing. It is unclear if catalyst durability, high-current performance, or mass activity (or a balance of these) is preferred for optimization. Robustness is missing in the future work. Perhaps even more important than scaling up is understanding how the catalyst responds to cold temperature, hot temperature, and load transients. DOE-prescribed testing should be done. It is good that the future work addresses durability studies and examining sources of voltage loss. However, these are fairly wide areas, and plans should be described in greater specificity.
- The proposed future work appears to align logically with the current project status and what is needed to bring the technology to the next stage. However, the primary focus should be on determining whether the catalyst can be successfully integrated into MEAs with high activity and performance and whether the catalyst is durable toward potential cycling, rather than determining whether the catalyst can be scaled up to the next stage for additional ALD process optimization.
- Future work needs to focus more on the verification of Ni stability and on the control of process variations.

Project strengths:

- This is a rare catalyst project with a well-established means of scaling up the material. The project has a concept that lends itself to high specific activity and mass activity, and has been able to execute both using ALD. The ALD process should be repeatable, and the results so far show that it is. This has been shown without wasting taxpayer money on over-engineering a system to accomplish prescribed repeatability targets. The project has taken care to remove excess Ni while still retaining the Ni needed for catalytic activity.

- The approach of using NW as a support system is good and has high potential to achieve durability targets. Moving to Co NW to minimize Ni content in the electrode, and hence minimizing the chance of Ni poisoning, is a good approach. The team is composed of highly qualified subject matter experts, which gives them a higher chance of the project's having a successful completion.
- This project has clearly demonstrated synthesis and scale-up of ALD-derived low-Pt loading electrocatalysts for oxygen reduction reaction. The project has done an excellent job characterizing properties and improving performance and has clearly identified remaining barriers.
- The unique catalyst structure, which has demonstrated mass activity in RDEs, exceeds the DOE targets by multiple factors.
- This project group is very experienced with working in this field, and they have chosen partners that have proven themselves capable of successfully completing this project.
- Project strengths include ALD scale-up and Pt/Ni compositional control.
- The novel structure catalyst allows unique vision into solving electrode issues.

Project weaknesses:

- MEA performance and durability are the clear areas of focus for the remainder of the project. A pathway for improved HCD performance is demonstrated, but approaches to improved durability are less clear.
- The project still needs to make greater progress in three areas: durability (to lower voltage window cycling), understanding (specifically of voltage losses at HCD), and testing (for robustness to various temperatures). Power density needs to increase substantially to become attractive to the catalyst and MEA suppliers that would develop the technology further. The perspective of a catalyst-coated membrane or MEA supplier would help to accelerate electrode design.
- Durability would be expected to be higher for an extended material. The use of carbon negates some of the advantages of using an extended-surface material; carbon corrosion and material agglomeration issues still remain.
- Catalyst activity and performance in MEAs are highly suppressed relative to RDEs. Catalyst–electrocatalyst cyclic durability is not sufficient. Catalyst characterization is limited after fuel cell testing and durability ASTs.
- The team has no plan to do durability cycle studies (load/humidity, start/stop), which could give them better information about catalyst stability under automotive operational conditions.
- This project needs to develop the process and procedures necessary to verify that Ni will not leach out of the catalyst layer over time, for all operating conditions that are anticipated.
- Catalyst size and the high-transition-metal content are weaknesses.

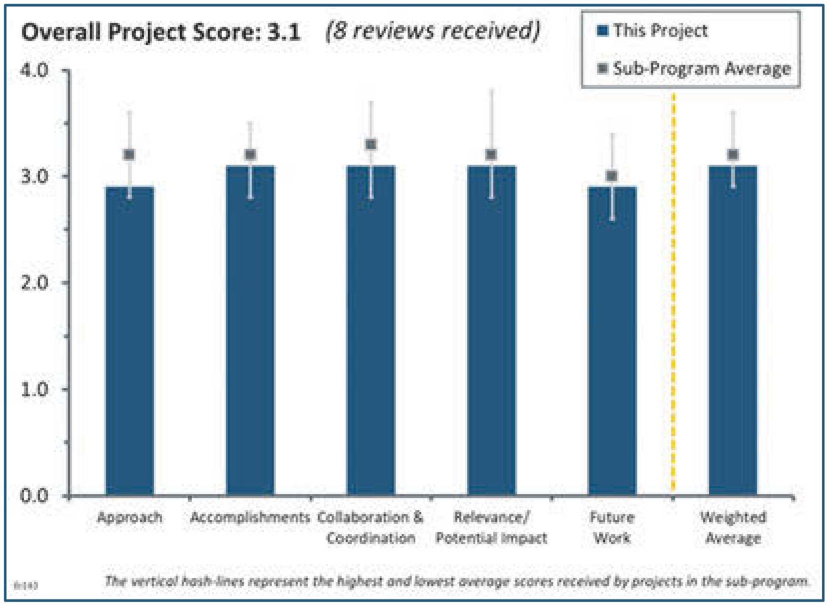
Recommendations for additions/deletions to project scope:

- Since mass activity measurements at 0.9 V are subject to variability, the intra-batch and inter-batch repeatability metrics might be more meaningful at HCD. Addition of a catalyst-coated membrane or MEA supplier might help to accelerate electrode design. It may be useful for the project to report whether there have been any problems that have arisen since using standard conditioning protocols.
- The project should propose alternative strategies beyond carbon to improve mass transport and HCD performance.
- Depending on the available time and funding, the addition of load cycling, humidity cycling, and start/stop cycling are suggested.
- Additional scale-up work and process optimization with the ALD partner should be halted until fundamental catalyst activity, performance, and durability concerns in MEAs are addressed. Significant additional focus should be placed on the catalyst cyclic durability assessment and the characterization of related materials. Integration into high-performance MEAs is also necessary to assess whether the achievement of rated power targets is feasible with the class of catalysts.
- If it is not already in the upcoming statement of work, the inclusion of image wires after metal AST is recommended, as is the confirmation of structural integrity.

Project #FC-143: Highly Active, Durable, and Ultralow-Platinum-Group-Metal Nanostructured Thin-Film Oxygen Reduction Reaction Catalysts and Supports

Andrew Steinbach; 3M

Brief Summary of Project:



This project is developing thin-film oxygen reduction reaction electrocatalysts on nanostructured thin-film (NSTF) supports developed by 3M. The aim is to exceed all U.S. Department of Energy (DOE) 2020 cost, performance, and durability targets through developing two different NSTF-based structures, nanoporous thin-film and ultrathin-film (UTF) catalysts. The electrocatalysts will be compatible with scalable, low-cost fabrication processes. The project will integrate the catalysts into advanced electrodes and membrane electrode assemblies (MEAs) that address traditional NSTF challenges, which include operational robustness, contaminant sensitivity, and break-in conditioning.

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach involves developing the ultrathin-film NSTF concept, with a particular focus on maintaining activity and durability, with very low-platinum-group-metal (PGM) loading. This approach is essentially an extension of what 3M has been doing for many years, but it has become more important since the recent demonstration that NSTF can be incorporated into dispersed catalyst layers.
- The down-select to the UTF approach made sense and seemed to help in evaluating other parameters such as Pt content and underlayers. The upcoming activity milestones are based on PGM content. There may be value in expanding the investigation of non-PGM sublayers.
- Progress toward the milestones is good. Even while the overall approach may not be viable, contributions to the understanding of catalysts and electrodes are good.
- 3M has been working on Pt and Pt-alloy catalysts deposited on NSTF supports for a long time, and it looks like the team still has issues to solve in terms of meeting the mass activity durability targets. 3M is continuing the approach in which Pt-based catalysts are deposited on NSTF supports (with various metallic underlayers) to achieve the DOE 2020 targets. The research is well supported through density functional theory (DFT) calculations and Monte Carlo simulation studies done by university partners.
- The approach continues to be primarily focused on developing more active NSTF-based catalysts, which is good, but it does not address the primary barrier to the success of NSTF in polymer electrolyte membrane fuel cells (PEMFCs), which is operational robustness.
- The project team’s approach is to develop radically different, catalyst layer physical structures, mostly on the micron-size level, as shown by the whisker structure on slide 4. This structure is vastly different from the structures made using conventional Pt/C catalyst materials; thus, the modeling should focus on the mechanisms/limitations of the transport properties of the whisker structures in fuel cell operation, rather than on the catalyst activity. It appears as if Johns Hopkins is doing this, but no data/modeling results were reported.

- The approach addresses fuel cell cost and durability barriers. The approach is focused on reaching activity and performance at high-power targets. Barriers specific to the thin electrode structures and NSTF-type catalysts, such as robustness and long conditioning times, are not addressed in this project. The DFT modeling has helped guide the experimental effort. The project goals indicate that the active area will be increased by integrating catalysts with higher-area supports. Efforts to integrate catalysts with higher-surface-area perylene-red supports (i.e., through higher whisker density or longer whiskers, etc.) are not apparent. Using Ir as an underlayer increases reliance on scarce resources.
- The project is aimed at mass activity, which is more related to catalyst activity. However, one of the most critical barriers of this type of non-ionomer catalyst layer is operational robustness, particularly hydration sensitivity. Any attribute of this barrier was not addressed in the project, and neither was any approach discussed. The requirement of long-time MEA conditioning is also a significant problem.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- 3M has been admirably thorough and diligent in investigating a huge range of different material additives to enhance the activity and durability of the PtNi UTF catalyst. Extensive work on Ir underlayers has helped to determine mechanisms by which UTF can be stabilized, though replacement of Ir with a non-precious material is needed for applications. So far, attempts to replace the functionality provided by Ir using alternatives such as Ta have been only partly successful. Much of the work has been performed using Pt NSTF (not alloys). Limited work with PtNi alloys suggests that the alloy composition will have to be re-optimized for use with the new metal underlayers. Results this year did not approach the high goals set for mass activity.
- The project has produced a good number of data with respect to catalyst preparation, characterization, and performance evaluation. 3M's UTF 31Pt/26Ir catalyst, especially, showed durability under catalyst and support accelerated stress test protocols. However, it appears that the mass activity of this catalyst is much lower than the 2017 result shown for the UTF Ir/PtNi catalyst. It would be good to see the Pt and Pt-alloy dissolution data, since the research is producing ultrathin catalyst layers.
- Milestones are being achieved, and several materials are being made; the down-selects seem behind, but some interesting materials are being developed. Some of the stability analysis should be better supported in terms of post-testing analysis—fuel cell effluent analysis and decomposition rate would be helpful.
- As usual, the amount of work presented and apparent progress are impressive. However, there are minimal results with respect to operational robustness, which should be occurring as well—especially with the addition of the FC-155 project.
- The mass activity of the effect of Cr is good: 0.57 A/mgPGM. The Ir underlay was interesting, and the Pt base-mass activity was significantly improved. However, it is not good that it is PGM-based.
- The project has made progress toward increasing durability of UTF catalysts. 3M has met the DOE target for a high-power performance of 0.125 gPGM/kW, with an Ir underlayer system. 3M has not yet been able to use the same catalyst to achieve all the activity, high-power performance, and durability targets. Mass activity of the durable systems has been lower than predicted, based on modeling. Mass activity is far from the project target of 0.80 A/mgPGM.
- Although the 0.44 A/mg PGM milestone can be avoided in the go/no-go decision, it currently seems unclear how it would be met. Reducing the Ir content appears critical but has been commented on in the "Remaining Challenges and Barriers" slide. The inclusion of durability data in the "Technical Backup" slides is appreciated. While the Pt/Ir data show promising durability, there is significant loss for the Pt/Ta materials. If the Ir underlayer cannot be reduced, the use of a non-PGM underlayer to improve PGM-based performance may come at the expense of durability.
- The accomplishments should have shown more fuel cell data; only one polarization curve, with a very low open circuit voltage (OCV) of 0.85 V and two-minute hold time per data point, was shown. Also, the membrane type was not shown, and low OCV is indicative of ultrathin membranes, which could have lifetime/fuel utilization issues.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The project has excellent collaboration with two universities to perform modeling studies and two national laboratories to perform characterization studies. In the second year, the project has produced significant modeling data.
- 3M is effectively collaborating with the partners. There is a good collaboration between the modeling effort and the experimental effort.
- It is good to leverage academia (i.e., universities) and national laboratories, in addition to the industry principal investigator.
- This project is excellent with project partners. The contributions of the partners are clear, as is the significance of these contributions. However, it is not very evident if there was good collaboration with a related 3M project (FC-155).
- The collaboration with Argonne National Laboratory and Oak Ridge National Laboratory is helpful for utilizing advanced characterization capabilities. The collaborations with Purdue and Johns Hopkins University appear helpful to improving understanding of the underlying factors that determine performance and durability, although, given the high experimental throughput in this project, it seems that direct experimental measurements could provide most of the critical data needed to build this understanding.
- The collaborator contributions were clear. The need for modeling may be limited with the increasing focus on cell performance, but it was appropriate, particularly with the earlier emphasis on simulation and a combinatorial approach.
- Collaboration is minimal but well executed.
- There were only university and national laboratory partners; modeling results from partners were limited to catalytic activity modeling, not transport modeling, which this project needs. This project would benefit from an original equipment manufacturer (OEM) partner to demonstrate MEAs in an independent laboratory.

Question 4: Relevance/potential impact

This project was rated **3.1** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The development of improved PGM-based catalysts is highly relevant and should continue to be a top priority of the Hydrogen and Fuel Cells Program (the Program). While NSTF has historically been of limited relevance owing to concerns associated with conditioning and robustness, recent progress on dispersed NSTF catalysts has addressed this issue.
- The research is highly relevant to the technical targets from the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan. The PtIr UTF catalyst has already met the technical targets for electrocatalyst and catalyst support durability metrics and exceeded the DOE 2020 target for PGM content.
- The project is relevant to the FCTO and addresses key barriers for fuel cells. The project advances progress toward meeting the Fuel Cell R&D sub-program's targets and goals for cost, PGM loading, and durability. For commercial impact, break-in time must be reduced.
- If this is a catalyst project, then impact is routine, similar to other catalyst alloy projects. The potential of this project is the catalyst-layer structure and mass transport behavior, which has the potential to be tailored and controlled rather than having a fixed and arbitrary structure like conventional Pt/C has.
- The project addresses catalyst activity, cost, and durability. The project clearly supports and advances the goals and objectives of the Program.
- Besides good technical progress of NSTF, a critical problem is the robustness of this non-ionomer catalyst layer and sensitivity toward hydration of the catalyst layer. The project does not address this problem and does not set any attribute related to this operational robustness.
- NSTF catalysts can potentially have a major impact on PEFCs. However, the primary barrier for NSTF in PEMFCs is operational robustness. This project does not appear to address that issue significantly.

- The materials science component of the project is good, but overall, the underlying concept may not be implementable.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- It is good to explore the mechanism of effective integration with Ir or Ta underlayers. This has the potential to improve the catalyst performance if the PGM amount in the underlayers is properly controlled.
- Much of the "Remaining Challenges and Barriers" slide addresses the underlayers (Ir reduction or non-PGM) and performance. The "Key Future Work" slide is appropriate and follows logically.
- Future work is clearly planned and defined.
- The proposed future work mitigates risk by looking at methods to reduce PGM loading by replacing Ir with PGM-free underlayers and by using higher specific activity alloys to deposit on Ir underlayers. If 3M can replace Ir with a PGM-free underlayer and get similar performance from the Pt, the project can achieve its targets of 0.8 A/mg PGM, with <20% loss and MEA PGM content of <0.10 g/kW apparent. The proposed future work does not address known weaknesses of long break-in time and poor robustness/low-temperature operation of thin-film catalysts.
- The project includes a solid future work plan but is missing computational work on underlayers. High-current-density work would be good, as well as degradation product analysis.
- The proposed future work is highly ambitious owing to insufficient time, since the project will end in March 2019.
- The proposed future work is more of the same, but it should include more durability and performance stability data.
- The proposed future work does not address operational robustness in a significant manner.

Project strengths:

- The project has the advantage of more than ten years of work on NSTF-based catalysts, which makes it possible to better understand the system and perform necessary surface modifications to achieve DOE technical targets. The project has already met most of the DOE 2020 targets for electrocatalyst and catalyst support.
- The project focus is in the right places. A large number of material combinations and parameters have been evaluated, and there is a clear understanding of the remaining project challenges. Further development of NSTF-based catalysts provides value and aligns with FCTO priorities.
- The 3M team has excellent testing capabilities and has been able to test a large range of candidate materials and structures, enabling significant learning and development of promising catalysts.
- The project's strength lies in the quality of the experiment, as well as the material fabrication process of physical-vapor-deposition-based catalyst layers.
- This project has excellent materials science development, electrode testing, and throughput.
- The strength of this project is related to its continued improvements on NSTF catalysts, with respect to both performance and durability.
- This project has potential with the ability to tailor the structure of catalyst layers.
- The high durability of the NSTF systems is a strength.

Project weaknesses:

- The structures are going on 20 years of demonstrations—better mass transport understanding should be key for future work.
- The approach relies excessively on Edisonian testing. For instance, while several surface modifier species have been investigated, there does not seem to be an explanation for how they were selected, other than trial and error. A more targeted research and development plan based on clear fundamental principles could be helpful.

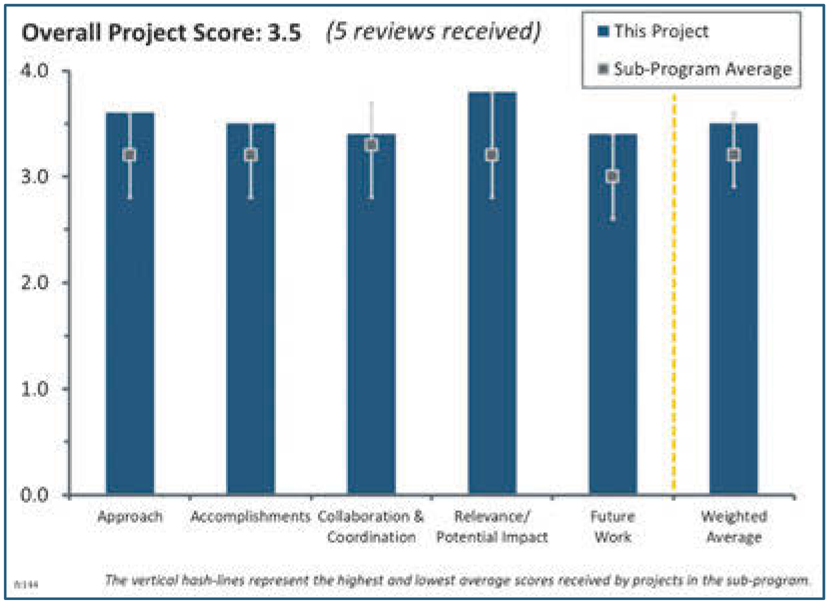
- Project weaknesses primarily center around performance and whether there is a clear path forward for improvement. Since a significant number of parameters have been evaluated, it may not be possible to meet higher targets (0.44 A/mg PGM) with the PtIr and PtTa systems being evaluated.
- There is minimal focus on NSTF catalyst layer development and (not surprisingly) little evidence of significant improvements in operation robustness.
- High current density and degradation mechanisms are not demonstrated, and cost is a factor.
- The project does not describe the scalability of the UTF catalyst. The durability of the UTF catalyst in short stacks may be an issue.
- The project avoided discussing one of the most critical technical issues of this NSTF technology.
- The long conditioning times required for these systems is a weakness.

Recommendations for additions/deletions to project scope:

- There may be value in expanding the examination of underlayers beyond the Ir and Ta presented. There may not be a need to continue model development, with the increased emphasis on cell performance and with the gap between experimental activities and the model prediction.
- Adding more modeling work on the transport mechanisms in the novel structures is recommended. More data on the stability of the fuel cell performance as operating conditions change (i.e., drive cycles) should be added.
- There should be more emphasis on addressing operational robustness so 3M can sell NSTF MEAs to PEMFC developers, not electrolyzer OEMs.
- Recommendations include (1) analysis of fuel cell effluent for degradation products to understand stability of composite metals and (2) theory analysis of future conductive underlayers.
- The project should focus on developing ionomer-free catalyst layers utilizing UTF catalysts.
- It is highly recommended that the project be redirected toward operational robustness of NSTF.
- Work to reduce conditioning times would be beneficial.

Project #FC-144: Highly Accessible Catalysts for Durable High-Power Performance

Anusorn Kongkanand; General Motors



Brief Summary of Project:

This project aims to reduce overall stack cost by improving high-current-density performance in hydrogen–air fuel cells that meet U.S. Department of Energy (DOE) heat rejection and Pt-loading targets. Investigators will maintain high kinetic mass activities and mitigate catalyst degradation using supports with more corrosion resistance than the current high-surface-area carbon (HSAC). The project takes a four-pronged approach: (1) improve oxygen transport with new carbon support, (2) reduce electrolyte–Pt interaction, (3) enhance dispersion and stability of Pt-Co particles, and (4) improve understanding and control of leached Co^{2+}.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project is undertaking very important work needed to ascertain a fundamental understanding of low catalyst loading. The project follows an excellent approach. The team's iteration of characterizing and then reiterating materials development is very appropriate. The project employs excellent and very appropriate characterizations and uses outside team members on the characterization side well.
- The approach is sharply focused on achieving DOE targets in cost, durability, and performance. These multiple targets are addressed by focusing a research effort on both low- and high-current-density performance via intelligent selection of catalyst, support, and integrating modeling in the optimization process.
- The project follows an effective approach to understanding opportunities with a number of promising concepts, including the accessible carbon supports, the ionomer and ionic liquid interface approach, ordered intermetallic alloys, and the effects of the cations. For the accessible porous carbons, the approach is supported via theory, imaging, comparison to a number of structures, measurement of key parameters, and correlations with respect to local oxygen proton properties. It was not clear whether the project team has modeled the expected optimum. Understanding the proton resistance versus oxygen resistance is very important to drive further development. Rather than maintaining volumetric ratios of carbon to ionomer, the project team should control the surface-area-to-ionomer ratio to maintain the assumed similar ionomer thickness levels.
- This project is addressing a critical issue of hydrogen contaminant detectors (HCDs) with a low-platinum-group-metal (PGM) catalyst. This project has a very good collaboration scheme among many partners.
- Some aspects of the approach appear very likely to help overcome barriers, such as the use of accessible pores and ordered intermetallic alloys. Much of the work has been devoted to these parts of the project. Some aspects of the approach, however, do not appear likely to help overcome barriers. The use of ionic liquids was premised on the need to have ion-conducting species near platinum that do not confine themselves on the platinum (e.g., ionomer). However, through the two-year history of the project, ionic

liquids have not delivered promising results. In situ visualization of cobalt and cerium cations has not yet provided substantial results. The slides provided still leave the possible contribution of this work uncertain. Greater knowledge of the model would be needed to understand what the impact of this work would be.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The concept of accessible porous carbon was well established in the 2017 DOE Hydrogen and Fuel Cells Program Annual Merit Review. The modified HSACs have been used to show that pore volume, in a particular nanoscale regime, results in enhanced oxygen transport as well as enhanced proton transport. High-current-density results for PtCo, supported on accessible porous carbons, show the effectiveness of past efforts. Ordered PtCo/KB clearly shows an improvement in lowering mass activity and electrochemical surface area losses during the electrocatalyst cycling. Results showing the reduced proton transport loss at high relative humidity, as well as for carbons that anchor platinum on the exterior of a primary carbon particle, are very nice to see, but they are familiar trends from the year before. Robustness was very well shown with polarization results for low temperature, as well as for low outlet oxygen concentration.
- Excellent progress has been made toward understanding the mechanisms of transport losses at high current densities and toward design of a durable catalyst and support. Most of DOE's targets are met or have been closely approached with a PtCo catalyst supported on the new durable HSAC mesoporous support.
- The project team is making more progress than would have seemed possible. Very strong momentum has been observed on both transport and durability, in which the team is surpassing targets.
- Task 1 is completed. Different carbon supports are also being tried out. In situ synchrotron X-ray diffraction (XRD) and the scanning transmission electron microscope (STEM) were good tools for optimizing the Pt_3Co. It was good to see evaluations of various equivalent-weight ionomers and also ionic liquid integration in the catalyst layer (CL). If the long-term evaluation of the ionic liquid is not in the scope of the project, then resources and time should not be invested in it. However, looking at promising results with in CL, it would be worthwhile to see the durability of the ionic liquid, which is something that DOE and the principal investigator (PI) can discuss.
- The project team is finding some observed correlations between key parameters, such as oxygen reduction reaction (ORR) activity versus mesopore volume. Good improvements were observed in transport and activity by the creation of appropriate pore geometry. However, there appears to be a tradeoff in durability that will be important to address. The project team found increased platinum utilization through the use of ionic liquid and a higher performance. It is unfortunate that the project does not have data from test periods longer than one week, as it will be important to understand the ionic liquid's stability.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- General Motors remains the driving force behind the project, with major contributions from Cornell University and the National Renewable Energy Laboratory (NREL). Cornell University appears to provide considerable help with PtCo stabilization, compositional analysis, and imaging. NREL provides considerable help with defining loss terms from fuel cell measurements. It does not appear that collaborations with 3M Company, Drexel University, and Carnegie Mellon University are as substantial as those from Cornell and NREL, which might be by design. However, the project could benefit from greater inputs from Drexel University and 3M Company if ionic liquids and perfluorinated imid acid ionomers can provide polarization benefits. The addition of these components to a CL is not likely to be trivial. Carnegie Mellon University appears to contribute three-dimensional imaging and modeling, most of which agrees with conclusions already drawn from other parts of the work.
- The project has some of the best collaborations that the reviewer has seen, in that each team member has a direct role and, more importantly, it relates directly to the project. Now that the project has shown the

importance of pore structure, it would be good to see the team working with someone who is more of an expert at controlling this going forward.
- Significant collaboration exists with a number of groups, including other industry representatives, national laboratories, and academics.
- There is excellent coordination between funded and non-funded partners. It is very clear who is doing what.
- This is a very well-coordinated effort between the team members.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The relevance of a catalyst project that focuses on improving high-current-density performance, especially over accelerated stress cycling, is self-evident. Power density and durability are well addressed in the Fuel Cell R&D sub-program targets. Better high-current performance can reduce the active area of the stack, which can have an impact on the overall cost of the stack. Using an ordered PtCo intermetallic to address durability is highly relevant toward enabling the use of high-activity materials.
- The project clearly aligns very well with DOE's research and development and the Fuel Cell Technologies Office's Hydrogen and Fuel Cells Program's 2020 goals. Improving HCD performance of the low-PGM catalyst is very important, and this project is investigating and modeling this with an optimized catalyst and CL.
- The project directly addresses and has made great progress to both understanding and solving the problems of transport losses at very low loadings and catalyst stability. This would make the project an unqualified success.
- The work is highly relevant and addressing a key technical challenge that is impeding progress toward lower catalyst loading. The project is ultimately achieving DOE targets in a manufactureable design.
- The project is very well aligned with the DOE goals and has potential for significant impact on technology development.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The project's proposed future work is a logical continuation of a previous effort. It combines accomplishments from the previous phase of the project in terms of the catalyst, support, and CL design to meet DOE's durability and low- and high-density performance targets.
- The project's future work is well planned and relevant. It will be important to optimize the catalyst for both activity and durability. It would also be good to see a slightly longer test on ionic liquid.
- The project's future work is appropriate, and it is winding down, which is a shame. As such, the project team is selecting final catalysts for membrane electrode assembly (MEA) delivery to DOE. It will be very interesting to understand the ionic liquid work better—especially its durability and retention.
- Models are mentioned, but details on how the models can be used and what benefit the models will create for the greater community are difficult to derive. Future work is focused on durability and high-current performance, which is appropriate. Nothing explicitly says that the ordered PtCo will be combined with accessible porous carbon developed earlier in the project, but presumably, that will be the case. The question-and-answer session revealed that durability testing with ionic liquid is outside the scope of the project, which calls into question why ionic liquid work should continue.
- If the ionic-liquid-integrated MEA will not be tested for durability, then not much effort should be put into it. The Fuel Cell Performance and Durability Consortium is showing very high ORR activities (~1 A/mgPt) in MEAs for commercial catalysts (e.g., Umicore) using more conditioning. This team should look into this approach and also investigate whether increased ORR activities after more conditioning has any effect on HCDs.

Project strengths:

- The project lead is an automotive original equipment manufacturer that has perspective on what needs to be done to commercialize fuel cell systems. The project team has developed a concept (accessible porous carbons) to address oxygen transport and proton transport losses at high current density, which can bring down the active area and cost of a stack. The project team has developed a material concept for durability, namely the ordered intermetallic PtCo. The project team has access to imaging, modeling, and tomography resources for a deeper understanding of catalyst phenomena.
- There is a clear focus on key technical challenges. There are strong collaborations incorporating the expertise of a number of groups. There is strong support of characterization and measurement on the experimental work.
- The project has a very strong team and PI who leads the project in a timely and efficient manner. The project combines the best expertise in synthesis, modeling, and evaluation of materials and fuel cells.
- The project has a strong team and collaboration, led by General Motors. The project team has undertaken balanced efforts on catalyst development and CL optimization.
- The project has great technical momentum with excellent teaming and characterization. The project follows a logical flow and performs relevant tests to prove or disprove this logic.

Project weaknesses:

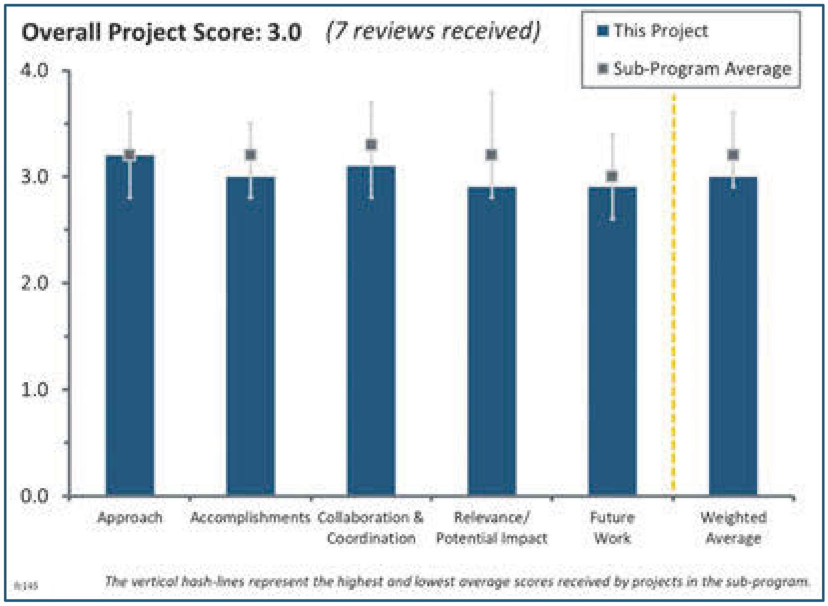
- There is only one catalyst candidate. Although many carbons supports are investigated, more catalyst candidates could have been better.
- The project team should benchmark against new commercial catalysts, which are showing very high mass activity in MEAs.
- Modeling appears to serve as a confirmation of what is already known. It is not apparent that the modeling is critical to the project. Ionic liquid and novel ionomer efforts do not appear to be “mainstream” to the rest of the effort. The project would be just as valuable without these work streams.
- The project team could have planned better for its successes. After showing the importance of pore structure, the project could have a better plan to control it. Similarly, the ionic liquid task has shown promise, somewhat to the project team’s surprise, but the team seems unprepared to do the next obvious steps: discovering whether it is durable, both chemically and physically (i.e., whether it “stays in there”).

Recommendations for additions/deletions to project scope:

- It is a well-thought-out project. No changes to the project scope are recommended.
- The project team should focus on the durability of ionic liquid in accelerated stress testing or remove ionic liquid work entirely. If modeling serves only as a confirmation of what is already understood, then the reduction of modeling efforts should be considered. Reporting should clarify the benefits expected from modeling cation transport.
- Obviously, the project team should follow up on the ionic liquid work. Also, it would be good to see some further work/investigation on the thesis that transport is taking place in condensed pores. This is very important to the fundamental understanding.
- The project team should work to increase the understanding of ionic liquid stability and durability.
- If ionic liquid in the CL is showing improved ORR, then it is worthwhile to investigate durability.

Project #FC-145: Corrosion-Resistant Non-Carbon Electrocatalyst Supports for Proton Exchange Fuel Cells

Vijay Ramani; Washington University



Brief Summary of Project:

Carbon's high electrical conductivity and low cost make it an excellent electrocatalyst support, but corrosion leads to kinetic, ohmic, and mass transport losses. This project is synthesizing doped non-platinum-group-metal (PGM) metal oxides as non-carbon alternatives. Along with being corrosion-resistant, the project supports would have high surface area, exhibit strong metal–support interaction with Pt, and demonstrate high electrocatalyst performance.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach addresses a critical barrier of durability and cost by attempting to provide a materials-based solution to the catalyst support corrosion experienced during fuel starvation and startup/shutdown conditions. The project is sharply focused on improving support durability. The project has been well designed and has demonstrated feasibility of the proposed supports. The investigation of these materials as anode supports, as well as cathode supports, would be beneficial.
- This project is looking at a fundamentally different approach to the support that could yield interesting results. With such a different approach, more fundamental modeling of the effects of the unique support properties on electrode performance may be useful.
- Pursuing non-carbon supports has long been a target to enable less system-based controls to mitigate carbon corrosion and start/stop concerns. The materials investigated and the synthesis methods explored merit further investigation.
- The approach is sound and effective.
- This project follows a clear approach, using doped metal oxides to replace carbon. The team is holding themselves to the general catalyst U.S. Department of Energy targets, which is a good thing; however, it would be good to see a conductivity target, as well as details about the team's progress toward such a target. This is in a milestone that the project team says the project has met, but this has not been reported. It is clear that conductivity is a limiting factor on performance, so it should be a clear metric against which the team works.
- New materials have the potential to improve durability by overcoming carbon corrosion. It is unclear whether these materials support and help improve Pt mass activity and overall performance, compared to carbon supports. Density functional theory (DFT) modeling could help lower the matrix of materials to try and add information to help other projects.
- The presentation does not clearly state how the project will achieve the end-of-project mass activity target of 0.3 A/mg_{Pt}, considering its current status of 0.05 A/mg_{Pt}.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has been able to develop high-surface-area doped TiO_2 supports with improved durability under start/stop cycling conditions compared to carbon supports. Rotating disk electrode (RDE) data indicates that the team can achieve oxygen reduction reaction (ORR) activity for Pt on doped TiO_2, which is higher than that for Pt/C. The project team has also developed Sb-doped tin oxide supports and performed durability tests with Pt/Sb–SnO_2 catalysts. The Sb-doped tin oxide supports showed much lower losses after start/stop cycling than Pt/C and higher performance after the cycling for Pt/Sb–SnO_2 than for Pt/C. The project team has been able to obtain electrochemical surface area values on the oxide supports comparable to those obtained for Pt/C. The initial performance of the Pt/Sb–SnO_2 was much lower than that for Pt/C. Activity for the Pt/Sb–SnO_2 should be reported. Performing a characterization of the pore structure would be beneficial. The beginning-of-life activity and performance at a high current density need to be improved. Humidity dependence and robustness need to be determined. The oxide supports may have more problems with flooding and startup at low temperatures. The strong metal support interaction offers the potential to increase durability during the catalyst degradation cycling protocol. Samples should be tested under the catalyst durability cycle to see whether the strong metal–support interaction (SMSI) has an impact on catalyst durability in the catalyst durability cycle.
- Great work is being done on demonstrating the durability and developing some of the understanding behind it. The team states that the supports can increase activity, but other than theory, there is not really much evidence toward that; other than RDE, an increase in activity does not seem to show in full cell testing.
- Both of the two down-selected materials show merit and meaningful improvements over the past year. In particular, the report on fuel cell performance and durability shows promise. However, the high resistances found in fuel cell tests and limited mass activity remain challenges with no clear path to overcoming.
- The team showed that a completely new non-carbon support could function in a polymer electrolyte membrane (PEM) fuel cell; this is a significant accomplishment. However, the MEA performance is not close to where it needs to be for this to be a useful support, although the team has made progress.
- Meaningful milestones and membrane electrode assembly (MEA) tests were accomplished, despite a delay.
- The ORR onset potential for Pt/Nb–TiO_2 and Pt/C seem to be identical. It is not clear why the mass activity is different, but neither is very close to meeting the DOE target of 0.44 A/mg_{PGM}. Other Pt/C catalysts have been shown to have much higher mass activities compared to the one shown here, but it is unclear why these mass activities are as low as they are. Of course, Pt/Co and Pt/Ni could surpass the mass activity targets. Pt/C is likely not an appropriate comparison for the mass activity target. Stability against the DOE/Fuel Cell Technical Team carbon corrosion accelerated stress test (AST) looks good. MEA durability looks good, although performance is lacking. The cause of the relatively low performance is unclear, but the Tafel region looks to have large losses. A voltage breakdown might be informative to separate additional kinetic losses versus additional iR losses versus a Pt/C baseline.
- Only one MEA test result for the startup/shutdown protocol is presented (on slide 14) for fiscal year (FY) 2018. The project team should perform more fuel cell testing.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The project collaboration is good for understanding the fundamental characteristics of supports and/or catalysts and for evaluating their fuel cell performance and durability. Both the objectives have been met with the collaboration involving a second academic institution (The University of New Mexico [UNM]) and an original equipment manufacturer (OEM) (Nissan Technical Center North America [NTCNA]), respectively.
- Collaboration between the partners appears to be going well. Collaboration with the Fuel Cell Consortium for Performance and Durability may be beneficial, especially concerning the optimization of the ionomer content, Pt–support ratio, and support structure/porosity to optimize performance.

- This project contains good collaboration with appropriate partners. One group is making supports, another the catalysts and fundamental characterization, and the OEM is doing the final testing characterization. It appears that Nissan is not sharing much data, and Nissan's work seems a bit opaque.
- UNM accomplished the DFT and some characterization, and Washington University (WU) completed the synthesis; it is unclear what entity did the RDE and MEA testing, including the 1.0–1.5 AST, but assuming it was Nissan, this seems to be a well-coordinated collaboration. At this point, it is hard to tell whether the DFT modeling is really being used in the synthesis activities.
- For a large project, this is a small team, although have most critical aspects seem to be covered. In particular, a ceramic company, or at least someone more familiar with the large-scale manufacture of support materials and the technoeconomics of support production, would be valuable.
- UNM and Nissan are providing complementary contributions. However, the project is missing capabilities with the modeling of electrode performance based on the catalyst properties.
- Collaboration outside WU and NTCNA is not clear; iterative interactions are also unclear.

Question 4: Relevance/potential impact

This project was rated **2.9** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Catalyst corrosion is a huge challenge, and this project is demonstrating a viable path to achieving high-potential stable supports and catalysts.
- The project is relevant. The potential impact will depend on the relative cost to implement these oxide supports versus the cost of current system mitigation strategies. It will also depend on whether the oxide SMSIs offer additional advantages in the catalyst degradation cycle (0.6V–0.95V), compared to carbon supports. The supports may be more relevant as anode supports than cathode supports.
- The project is fundamentally interesting and could potentially improve oxidation resistance of catalysts; however, it seems unlikely this catalyst will be useful for an automotive fuel cell because of the low performance. The impact of this project may ultimately be for higher-temperature fuel cells or electrolyzers.
- This project appears to be primarily addressing the durability issue with carbon corrosion. There is discussion about improving mass activity, but that does not seem to be much of a goal, and it is unclear what activities will lead to an improved mass activity. An increased mass activity does not appear to be a major focus of this project. Many of the state-of-the-art (SOA) numbers appear significantly off from what others consider to be the SOA. For example, the mass activity is listed at 0.07 A/mg_{PGM}, where PtCo, a relatively old material used in the Toyota Mirai, has a mass activity clearly upwards toward 0.4 A/mg_{PGM}, while other laboratory catalysts regularly show mass activities >0.44 A/mg_{PGM} (the DOE target). The end target for this project is only 0.3 A/mg_{PGM}, which, if attained, is still not even the current SOA. A similar discussion on PGM loading can be had. This project should be much more aggressive with its end targets. Improved catalysts that reduce the fuel PGM content is one of the critical areas in which this project can make a near-term impact; this potential impact includes higher activity and improved durability.
- Metal oxide supports are known to be stable under high potential cycling conditions, such as 1.0–1.5 V. However, the proposed mass activity target (i.e., the end-of-project value) is much lower (0.3 A/mg_{Pt}) than the DOE 2020 mass activity target of 0.44 A/mg_{PGM}. It is unclear from the presentation how the mass activity target will be achieved by the end of the project.
- The project does have relevance in terms of durability against carbon corrosion, but the team does not address other DOE targets. Durability against carbon corrosion is perhaps one of the least critical metrics in the DOE target tables because of the ability to mitigate through system control strategies.
- If successful, these supports might well be implemented. However, they seem far away from traditional supports, and carbon supports are continuing to make progress. Hence, it is doubtful that these supports will come close enough to carbon to make a difference.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- It is not clear that the team wants to go to higher Pt loadings on the support; because of the higher density of these supports compared to carbon, the current loadings are comparable to or higher than the volumetric loadings of Pt on carbon. The proposed future work addresses the key areas of increasing surface area of the support and MEA optimization.
- The proposed research is sufficient to overcome some of the technical barriers presented in slide 18.
- The project should concentrate on increasing the mass activity of the catalyst, which may have to include using an alloy such as PtCo. The DFT calculations should possibly guide the synthesis for higher mass activities; while conductivity is (and can be) an issue, the project needs higher mass activities.
- The future work appears to be focused on a continuation of the work performed to date. The proposed work is reasonable, but it does not suggest further improvements to some of the more critical barriers that are not specifically addressed in the project—namely, improvements to increased mass activity and rated power, as well as perhaps addressing flooding issues caused by the use of such a dense thin-film electrode.
- The project team needs to increase both the conductivity and the surface area of the supports. However, as the team pointed out, these are tradeoffs, and this will be difficult. Increasing the active area and translating RDE results to the full cell are good goals, but it is not certain that the team has a reasonable path toward this.
- Considering recent personnel changes, the role of UNM is unclear, considering recent personnel changes, but WU and NTCNA work is appropriate.
- The support may have properties that make it unable to achieve DOE targets in an MEA, such as sufficient conductivity, porosity, and hydrophobicity. The proposed future work may not address the shortcomings with regard to such properties.

Project strengths:

- The project has developed stable conducting oxide supports with good Brunauer–Emmett–Teller (BET) surface areas that enhance the stop/start durability.
- The project is pursuing a unique approach that could drastically improve support oxidation resistance. This approach could be useful for other types of fuel cells (particularly intermediate temperatures) and electrolyzers.
- This project's strengths include collaboration with UNM for modeling and a sacrificial support method for making high-surface-area metal oxides, as well as Nissan for durability testing.
- This project has demonstrated superior durability performance to the carbon corrosion (1.0–1.5 V) potential cycling AST.
- This project has demonstrated two supports that have shown promise for increased corrosion resistance and have reasonable electrochemical properties.
- This is a good collaborative team with an appropriate approach. The work and results on durability are excellent.
- The project has a great and proven approach.

Project weaknesses:

- The team is plateauing on what the project can do with these supports. The supports are already too resistive, and it is necessary to increase porosity and surface area, but doing this will only hurt conductivity further. It is not certain that the team has a pathway to increase intrinsic conductivity.
- There is a lack of a ceramic/support synthesis company to better assess options for large-scale synthesis and commercialization. There is also a lack of an impact on a number of DOE targets, with a primary focus on carbon corrosion issues.
- The catalyst made in this project does not show competitive performance in terms of mass activity, and there seems to be little in the plans to increase the mass activity to where currently available catalysts are.
- Based on the results reported so far, this approach will probably not simultaneously achieve all of the DOE 2020 targets for automotive fuel cells.

- The cost and manufacturing analysis, as well as material compatibility for the new supports, should be considered.
- There was difficulty in achieving mass activities higher than the value reported in FY 2017.
- The resistivity is a little bit high.

Recommendations for additions/deletions to project scope:

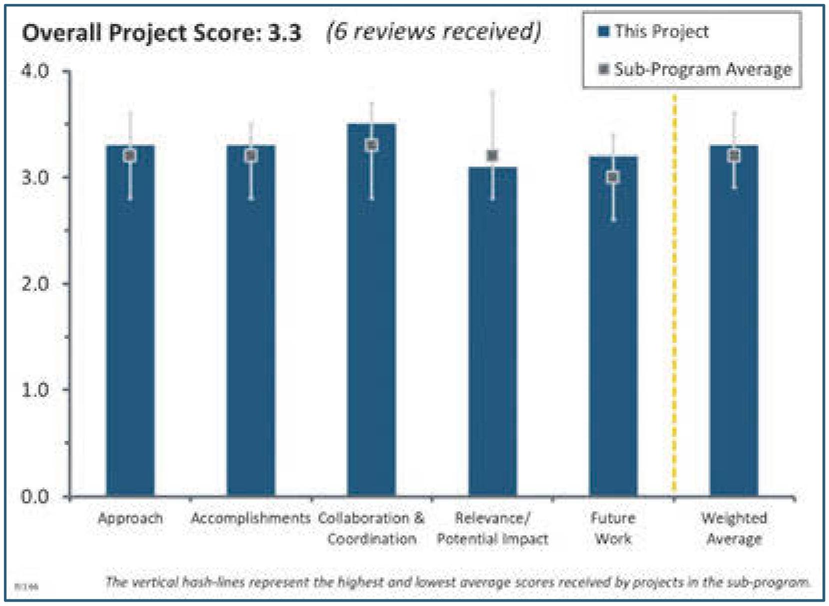
- The project team members need to understand the limitations that conductivity is placing upon performance. If the underlying support does not have that, the team can save themselves a good deal of time in adding the catalyst and making MEAs. In this regard, much of the future work includes the scale-up, manufacturing, and characterization of MEAs. If the underlying supports will not get the project where it needs to be, the team should put more focus on that future work.
- Electrode modeling could possibly be beneficial to this project. Exploring other applications should be considered because achieving the automotive targets for a PEM fuel cell does not seem realistic within the project timeframe.
- This project should concentrate more on improving mass activity; this could include the use of an alloy such as PtCo. Until mass activities are competitive, enhancing mass transport should not be a priority.
- Perhaps anode testing and validation should be substituted for the unclear UNM future contribution. Some technoeconomic analysis of the viability of these new catalysts should also be included.
- A focus on increasing mass activity to a relevant range, perhaps by investigating alloys, is recommended. A focus on electrode flooding issues is also recommended, and the concern over the relative humidity dependence on performance should be investigated.
- It is recommended that the project team add work to look at using these supports for the anode.
- The project should focus on more fuel cell testing.

Project #FC-146: Advanced Materials for Fully Integrated Membrane Electrode Assemblies in Anion-Exchange Membrane Fuel Cells

Yu Seung Kim; Los Alamos National Laboratory

Brief Summary of Project:

This project is developing advanced materials for fully integrated membrane electrode assemblies (MEAs) in anion-exchange membrane fuel cells (AEMFCs), enabling fuel cell cost reduction without sacrificing performance. The improved anion-exchange membrane (AEM) materials are based on highly conductive and stable hydrocarbon polymers. The project also aims to address challenges with integrating catalysts and AEMs into high-performance MEAs. The approach involves (1) preparing AEMs without aryl-ether linkages in the polymer backbone and (2) developing different ionomeric binders for anode and cathode.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The team has correctly identified the critical barriers regarding polymeric materials for alkaline fuel cells: polymer performance, stability, and durability in a fuel cell. The use of aryl-ether-free polyaromatic anion-exchange polymers is the correct approach to take. The ionomers developed in this project have been used as both the membrane and electrode binder in alkaline fuel cell MEAs. The project is well integrated with other AEM fuel cell efforts.
- This is a systematic approach to modifying polymer backbone and functional groups to reveal AEMs' weak points and systematically eliminate them.
- Critical barriers have been identified and are being addressed. The project is integrated with other relevant efforts on alkaline membranes and fuel cells. The project has previously identified cation groups that are more stable than the (hexyl) trimethyl ammonium cation being used in the current membranes. Degradation of this cationic group appears to be responsible for the observed losses in conductivity of about 50% in ex situ alkaline stability tests over roughly 2000 hours. It is not clear why the more stable cationic groups identified in earlier work (such as the resonance stabilized cations described in 2017) are not being utilized in the down-selected membranes. The hydrogen oxidation reaction (HOR) is sluggish in AEMFCs compared to polymer electrolyte membrane fuel cells (PEMFCs), and durable high-activity platinum-group-metal-free (PGM-free) HOR catalysts have not been developed, so the potential advantage of an AEMFC over a PEMFC has not materialized. A major weak link is the HOR catalyst, and this project has not addressed that barrier/weakness.
- The most critical barriers, such as membrane stability in an alkaline environment, AEMFC performance, and durability issues, have been addressed. However, more fundamental barriers for the application, such as the impact of carbonate/bicarbonate formation and its impact on membrane stability/properties and on performance and durability on a fuel cell level, have not been addressed.
- The approach to show membrane stability with ex situ aqueous experiments and steady-state H_2–O_2 tests is okay for initial screening but far from conclusive. Factors such as drier conditions, voltage cycling, and

humidity cycling must be considered. The approach of using model compounds to screen for ionomer adsorption on Pt-Ru seems reasonable, but the team needs to verify that density functional theory (DFT) results correlate with fuel cell performance. Also, the team should look at non-PGM catalysts for the adsorption studies. The approach of using diallyl phthalate (DAP) polymers is questionable. They are very brittle in polymer electrolyte membrane systems. It is not clear why AEM systems would be any better.

- The project's approach is okay, but the major motivation for AEMFCs is to use non-PGM catalysts; however, this project is doing very little in this area. It is understandable that a polymer chemist wants to focus on membrane development, not catalysts, but then it is questioned whether the project title should be "Advanced Materials for Fully Integrated MEAs in AEMFCs."

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Progress has been good and noteworthy. The project team has met or surpassed many/most of the DOE fourth quarter (Q4) 2017 metrics, including membrane area-specific resistance, AEMFC performance, and AEM durability. Materials have been screened and down-selected—an appropriate approach that has proven to be successful. Numerous MEA fuel cell polarization plots were shown during the Hydrogen and Fuel Cells Program Annual Merit Review (AMR) presentation, an indication that significant membrane/polymer progress has been made. The team has nicely addressed AMR comments from last year, including the investigation of non-PGM electrode catalysts. There is a good effort here by the team. The project end date is approaching, so the AMR presentation included numerous MEA performance plots.
- The project has made significant progress in the area of alkaline membrane durability and AEMFC performance. The project has exceeded AEMFC performance targets and is approaching durability targets. Work from this project has been instrumental in the increased understanding of AEM durability issues and catalyst alkaline–ionomer interactions. The work investigating the interactions of ionomer phenyl groups with the HOR catalysts, and the resulting development of skewed aromatic rings to limit phenyl adsorption, are major contributions to the field.
- As shown on slide 3, performance goals have been met or exceeded. Durability goals have nearly been met and are in progress.
- Very good progress has been made in terms of demonstrating high-power density. The down-selection process in finding promising candidates for stable membranes and suitable ionomers in the electrode led to a number of promising materials. The low PGM loading on the anode side is a very promising result. However, more results should be generated/shown regarding the properties and aging behavior of membranes and electrodes, such as changes in conductivity, membrane integrity/mechanics, and catalyst structure. The impact of ink preparation and the structure of the electrodes could be carved out more clearly.
- As far as AEMs are concerned, the beginning-of-life (BOL) performance and steady-state durability after 500 hours are on the right track. The mechanical durability and robustness at dry conditions cause concern. The high performance loss after 500 hours steady-state is very concerning, especially with no specific ideas provided to address the degradation. The accomplishment of identifying phenyl-group adsorption as a limiting factor is nice, but not surprising.
- There is good progress, especially with respect to studying degradation mechanisms. However, important aspects, such as air tolerance, continue to be ignored. It was stated that this concern has been addressed by having a back-up slide with an air polarization curve. However, the test was run with CO_2-free air. This is concerning since the major concern with air is CO_2.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), Argonne National Laboratory (ANL), and Rensselaer Polytechnic Institute (RPI) form a complementary and complete team

on making functional groups, the polymer backbone, modeling, and the catalysis of alkaline electrolyte membranes. There was no redundancy, and the team was well coordinated, with a reasonable budget.
- Collaborations within the project are going well. The project appears to be coordinating with an unnamed industrial partner, and coordination with the National Renewable Energy Laboratory and others in the overall field of AEMFCs is apparent.
- The project team is strong. SNL and RPI provided ionomers. ANL provided low-loading catalysts. Non-funded partners such as Technion also provided analysis.
- All major laboratories, institutes, and universities in the field seem to collaborate. The transfer of materials and data seems effective.
- The contributions from project team members is clear, and there are many interactions with others.
- The project is a collaborative effort with LANL as the lead, with SNL, ANL, and RPI performing support roles. The roles of SNL and RPI are obvious (i.e., polymer synthesis), whereas the ANL tasks were not well defined/explained. There are numerous other non-funded partners on the project, as per slide 15 in the AMR presentation. Their level of effort and the importance of their contributions was not clearly explained during the presentation.

Question 4: Relevance/potential impact

This project was rated **3.1** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Over the years, AEMs were considered intrinsically unstable. Thanks in no small part to this project, the stability of alkaline membranes has been greatly improved and will continue to be improved through rational improvements. This will open the door to inspecting the value of AEMFCs based on measurements, not guess work. Although a long way remains to an AEMFC, there have been some very interesting uses of AEMs in fuel cells, in particular, the use of a fluorene unit to make high-power (1.5 W cm^2) AEMFCs; another surprise is a self-hydrating bipolar membrane fuel cell that uses a cation exchange membrane and an AEM (see the *Journal of Power Sources*, vol. 299 [2015], p. 273–279).
- There is a need to examine/develop durable alkaline fuel cells that produce high power without the use of precious metal catalyst electrodes. The project team has made excellent progress in developing a high-power alkaline fuel cell and is investigating new AEM polymers with improved chemical stability, which is important. The team is also modeling water transport in an operating MEA, an issue that needs such attention.
- Alkaline exchange membrane fuel cells have potential for reversible fuel cells, where pure oxygen that is generated during the electrolysis step can be utilized in the fuel cell mode and can potentially enable PGM-free oxygen evolution reaction/oxygen reduction reaction catalysis. The project area of alkaline exchange membrane fuel cells is not well aligned with the transportation focus of the Fuel Cell Technologies Office. AEMFCs have several issues, the largest one being operation with air and the conversion of the membrane to carbonates, which has a large impact on membrane conductivity and performance. Other issues include HOR performance (leading to use of PGM-based catalysts) and lower power densities than PEMFCs.
- The project and its findings help in understanding the fundamentals of AEMFCs. However, the general feasibility—whether AEMFCs can be operated under ambient conditions and can contribute to reduced fuel cell costs by making PGM catalysts obsolete—has not been addressed; therefore, the progress toward the overall DOE goal cannot be assessed.
- AEMFCs are an interesting low-technology-readiness-level technology, which could have a major impact. However, this project is primarily limited to polymer-development progress that is necessary but not sufficient.
- It is difficult to assess relevance without a targeted application. Assuming an automotive application, the relevance is fairly low, as the trajectory for system cost and power density does not match that of PEMFC systems, which will not require carbon dioxide scrubbing or a complex water management system.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The future work outlined on slide 17 is all good: synthesis scale-up, non-PGM catalysts and reinforcing membranes, and further work to identify durability-limiting factors. In terms of durability, both the chemical instability of the polymer and the effects of CO_2 from the air on the anion (hydroxide or carbonate) type are the most important factors to address to make AEM fuel practical.
- Many remaining barriers are addressed, and it seems necessary to upscale the material synthesis. It would be helpful to focus also on catalysis, electrode preparation, and the analysis of the resulting electrodes.
- The proposed future work is mostly appropriate for the time remaining in the project; however, work with more stable cationic groups with a fluorene backbone would be good to add.
- The proposed future work is good since it claims the project will focus on durability and non-PGM catalysts.
- Future work will focus on synthesizing the down-selected AEM ionomer in larger quantities, completing MEA performance tests, and finishing up durability testing. There is a need to establish some kind of accelerated stress test (AST) for AEM durability to replace a constant current (or voltage) hold test.
- The top priority should be to identify the durability-limiting factor(s). The demonstrated 200 mV voltage loss in 500 hours of steady-state testing with platinum electrodes is far from acceptable. No scale-up should be done until it is known there is a semi-durable product. No indication of ideas or concepts to address the durability problem was presented.

Project strengths:

- The project addresses an important subject: the development and testing/evaluation of polymeric materials for the membrane and electrode binder in alkaline fuel cell MEAs. The project team has made considerable progress in meeting the project milestones and go/no-go decision points.
- One strength is the encouraging demonstrated BOL performance in oxygen- and carbon-dioxide-free air. This is a strong team, and there is interest from the fuel cell community in technology transfer. The fundamental approach to electrode ionomer selection is a strength.
- There is broad and good collaboration between all institutions involved. Good and promising materials and analytic capabilities are available.
- The strengths of this project are the innovations to improve stability and performance of fuel cells with anion-conducting polymers.
- This is a well-coordinated project that has done seminal work in the area of AEM durability.
- The strength of this project lies in the polymer chemistry.

Project weaknesses:

- The PI claims to have met a major AEM target (0.6 V at 0.6 A/cm^2), but this was *not* done at the required catalyst loading. In fact, the catalyst loading is >10x higher than the target, which is 0.1 mg PGM/cm^2 (p. 42 of the Multi-Year Research, Development, and Demonstration Plan). An 11,000-hour stability test has not been completed, since the conductivity was not stable during this period of time. Also, the time limit for AMR presentations should be better observed. There was insufficient time left for questions, and there are many questions when one makes big claims with materials that do not really meet the metrics.
- Membrane durability remains unproven at realistic, non-steady conditions. There is high voltage degradation, even with platinum electrodes and steady-state conditions, and there is no plan shown to address this weakness. Other weaknesses include a lack of adsorption studies with non-PGM electrodes and no ionomer durability.
- There were no obvious weaknesses in the project tasks and timeline. The team has yet to show good fuel cell performance with a non-PGM cathode catalyst. AEMFC durability continues to be an issue. There is no established method of assessing long-term durability in a short-term AST.
- AEMFC applicability to transportation applications is questionable because of problems with the carbonate/bicarbonate formation when operating on air.

- This project cannot contribute to answering the question of whether the fundamental problems in AEMFCs (e.g., CO_2, anode kinetics) can be overcome.

Recommendations for additions/deletions to project scope:

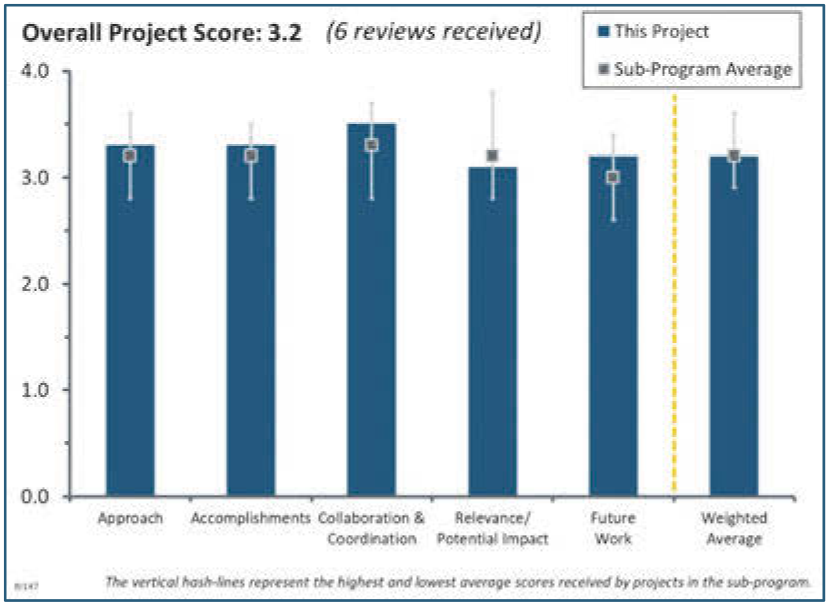
- It is recommended that the project continue to focus on MEA testing. Using a PGM-free cathode catalyst and setting specific performance targets for the membrane and binder are suggested. There may be a need to optimize on the conductivity/ion exchange capacity and thickness of the membrane in an AEMFC MEA. Right now, the PI is using a 40-µm-thick membrane. It would be interesting to see if a thinner membrane could be used (with reinforcement) for mechanical strength.
- The team should hold off on scale-up until durability issues are understood. The team should focus on the root cause of performance losses. The team should add to the project scope: membrane durability at dry and dynamic conditions (e.g., relative humidity, temperature, voltage cycles), membrane mechanical characterization (e.g., swelling, strength, stiffness), and DFT adsorption studies on non-PGM catalysts.
- Work with cations with resonance-enhanced stability and a fluorene backbone is recommended.
- It would be helpful if the preparation methods and the structure of the electrodes had an impact on the performance and durability.
- This work should be continued so that the team has the chance to address stability in more detail.
- Exaggerated claims should not be made. One should not claim to have met DOE milestones when that has not actually been done. The use of PGM catalysts, for now, is understandable. However, very high loadings should not be used.

Project #FC-147: Advanced Ionomers and Membrane Electrode Assemblies for Alkaline Membrane Fuel Cells

Bryan Pivovar; National Renewable Energy Laboratory

Brief Summary of Project:

Alkaline membrane fuel cells (AMFCs) offer promise for improved performance and decreased cost. This project aims to develop novel perfluoro (PF) anion-exchange membranes (AEMs) with improved properties and stability, employ high-performance PF-AEM materials in electrodes and as membranes in AMFCs, and apply models and diagnostics to AMFCs to determine and minimize losses (water management, electrocatalysis, and carbonate-related). Researchers will synthesize, characterize, and optimize AEMs and fuel cells for performance and durability.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This project takes on the difficulty of AEMs with the added difficulty of perfluorocarbon synthesis. Although results have been slow to come, the team members have not let "any grass grow under their feet" but have been making many difficult synthetic changes to find answers to their difficulties. The outstanding work with ethylene tetrafluoroethylene (ETFE) perfluorinated membranes with grafted functional groups by Varcoe (University Surrey) and Mustain (University of South Carolina) showing 2 W and 5 A/cm^2 gives incentive to continue this work to make a stable fluorinated AEM.
- The team is examining new anion-exchange polymers as membranes and electrode binders for alkaline fuel cells. The project is a collaborative effort with the National Renewable Energy Laboratory (NREL) (the lead organization), Colorado School of Mines (CSM), University of Tennessee (UT), and Lawrence Berkeley National Laboratory (LBNL). The tasks for each team partner are well defined and include polymer synthesis, materials fabrication and characterization, and mathematical modeling. The project is 70% complete. The overall project objective was not clearly defined in the slides, although milestones and go/no-go decision points were listed. No milestones were identified beyond September 30, 2018, even though the project does not end until March 2019, which was surprising.
- The most critical barriers, such as membrane stability in an alkaline environment and anion-exchange membrane fuel cell (AEMFC) performance and durability issues, have been addressed. However, more fundamental barriers for the application, such as the impact of carbonate/bicarbonate formation and its impact on membrane properties, including stability, and on fuel cell performance and durability, have been addressed only to some extent.
- The work addresses the performance and durability of AEMFCs. A PF-based AEMFC provides some potential advantages for phase separation to improve conductivity and for water management. The project still appears to focus on alkylammonium cations, even though the work indicates these cationic groups are degrading and more stable cationic groups have been identified in previous work.
- Go/no-go criteria of $\leq$0.1 ohm cm^2 is five times the polymer electrolyte membrane (PEM) target, with no plans or approach shown for how to reduce it further. It is not clear how to assess whether the technology will be competitive with PEMs. The approach of using accelerated ex situ tests is good. The project focuses

on using temperature as an accelerating factor; the team needs to validate whether 140ºC is too big of a hammer or whether the results correlate with in situ testing. Also, the team could consider low relative humidity (RH) as another option for acceleration. There is no clear approach to improving quaternary ammonium (QA) stability. CO_2 cycling is a good approach to assessing the CO_2 tolerance. The approach to focus on the impact of electrodes on water management is good—which is critical for AEMFCs. It is unclear how AMFC modeling will affect materials development.

- The project is focused on the major issues of AEMFCs, including performance, durability, and air tolerance.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The work by NREL looking at water management in AMFC systems has led to significant performance improvements. The ETFE-based electrodes prepared with the solid ionomer powder method have shown good improvements. Durability has improved but is still an issue with the materials shown. The project has met its performance milestones to date. A performance milestone is upcoming for the Gen 3 polymer, but insufficient data indicating the status or progress toward that milestone was provided.
- Very good progress has been made in terms of demonstrating high power density. Very good work was demonstrated, and many useful insights were generated through the comparison of the different electrode preparation processes and the impact on performance. However, the different behavior cannot be fully understood, especially when comparing to the results of FC-146. The results regarding the back diffusion of water and the related flooding issue are also important.
- The project showed impressive progress in many areas.
- There have been many unexpected problems during this project, but the team is working to resolve them. The ETFE work gives hope for fluorinated AEMs, but "the jury is still out." The team's modeling is showing that carbon dioxide from air may be a "show stopper" for an AEMFC in air. However, a fluorinated AEM may have uses outside of fuel cells or possibly in a fuel cell with a bipolar membrane that uses the fluorinated AEM (see Sikan Peng, "A self-humidifying acidic-alkaline bipolar membrane fuel cell," *Journal of Power Sources* 299 (2015): 273–279, doi:10.1016/j.jpowsour.2015.08.104).
- Progress has been satisfactory, although somewhat slower than expected based on the qualifications and experience of the research team. Too much time and emphasis were placed on a durability test that is not used by the AEM community and that has not been sufficiently correlated with simple high-temperature alkaline soaking tests that are used by the majority of AEM researchers. The Gen 2 polymer did not work well as an electrode binder compared to an ETFE material that has been developed and tested by others. Fuel cell tests with a PF-AEM catalyst-coated membrane were lackluster. The modeling work was satisfactory. The issue of carbon dioxide build-up in recirculated hydrogen was brought up but not addressed. There was insufficient comparison of the principal investigator's (PI's) AEM(s) and those in the open literature. There was no clear advantage presented in the PI's films in terms of enhanced transport or mechanical properties or in the polymer's chemical stability.
- The project is barely meeting not-so-challenging area-specific resistance (ASR) targets, with no clear plan for further reduction. The results to show improved stability of tether are good, but QA degradation is still a big problem. Testing and models confirm that carbonate is a big issue, but no materials of operating strategies were proposed to address this—it looks to be a fundamental issue with QA-based AEMFCs. There are major issues with the PF-AEM electrode used in this study, especially in terms of stability. It is unclear whether this is a fundamental issue with PF design or whether some of the issues could be resolved with optimization. All performance data shown was in oxygen—not air—with high loading platinum catalysts. The stability of the Gen 2 AEM/ETFE system was shown for only 15 hours in H_2/O_2—and performance was nowhere near the target in those tests. It is unclear how AMFC modeling is being used to support development; there is no model validation with data.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- This collaboration of NREL, LBNL, Oak Ridge National Laboratory (ORNL)/UT, CSM, and 3M covers all aspects of the project in a complementary and effective way. The project is also supplying membranes to a large number of others, which promotes the technology.
- The collaborations with multiple project partners are clear and appear to be productive in all cases. Additionally, there are obvious significant collaborations with others outside the project.
- The collaborators and their roles are clearly defined, and the most important universities, laboratories, and companies that can contribute to the project's success are involved.
- Collaboration is evident with others in the AEMFC community, and NREL has provided a service to the community by providing their Gen 2 membrane to others working on AEMFC catalysis. It is not clear how the modeling results are affecting the rest of the effort. The interactions have appeared to be one way: the experiments provide data to the modeling effort. The project team has not shown evidence that modeling is providing any guidance or suggestions for improving the experimental effort (e.g., for water or carbon dioxide management).
- The contributions from CSM and UT were not explained or presented. Most of the presentation was focused on small molecule chemical stability and membrane electrode assembly (MEA) fabrication, testing, and modeling. It was unclear if/how the modeling results were influencing the direction of the experimental work. The modeling work has not provided new information that would help the PI to synthesize new polymers and fabricate new membranes with a preferred set of properties and/or a particular structure.
- It is unclear how LBNL modeling work fits in with the rest of the project, whether the project team could meet project milestones without this modeling work, or which results—if any—came from CSM and ORNL/UT.

Question 4: Relevance/potential impact

This project was rated **3.1** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project has made great strides. There is no "payoff" yet, but it would be a reasonable approach to lowering costs if using non-PGM catalysts in liquid alkaline translates to AEMFCs. However, this team suggests that carbon dioxide from air may be a "showstopper" for use of AEMFCs in air.
- There is a need to examine/develop alkaline fuel cells that produce high power without the use of precious metal catalyst electrodes. The PI is investigating new AEM polymers with improved chemical stability, which is important. The team is also modeling water transport in an operating MEA, an issue that needs such attention.
- It still remains to be seen whether AEMFCs will have significant impact because, despite the substantial progress, there are still significant barriers to overcome.
- AEMFCs have potential for reversible fuel cells, where pure oxygen generated during the electrolysis step can be utilized in the fuel cell mode, and can potentially enable PGM-free oxygen evolution reaction/oxygen reduction reaction catalysis. The project area, AEMFCs, is not well aligned with the transportation focus of the Fuel Cell Technologies Office. One issue with AEMFCs for transportation is operation with air and the conversion of the membrane to carbonates, which has a large impact on membrane conductivity and performance and requires additional system components to scrub carbon dioxide from air. Other issues include hydrogen oxidation reaction performance (leading to use of PGM-based catalysts with higher loadings than polymer electrolyte membrane fuel cell [PEMFC] anodes) and lower power densities than PEMFCs.
- It is difficult to assess relevance without a targeted application. Assuming it is automotive, the relevance is fairly low, as the trajectory for system cost and power density do not match that of PEMFC systems, which will not require CO_2 scrubbing or a complex water management system.

- The project and findings help with understanding the fundamentals of AEMFCs. However, the general feasibility of whether AEMFCs can be operated under ambient conditions and can contribute to reducing fuel cell costs by making PGM catalysts obsolete has not been addressed. Therefore, the progress toward the overall DOE goal cannot be assessed.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The project team has a good plan. One recommendation would be to add ionomer development work based on the obvious challenges with electrodes and catalyst layers.
- The plan on slide 21 is good. The project team should try the Gen 3 polymer as soon as possible. The team should study stability (etc.) and other effects of carbonate and should optimize electrodes and performance with new materials.
- The suggested focus on increased stability is appropriate. More information on which cation groups are going to be pursued would be beneficial. The suggested electrode optimization studies are appropriate. It would be good to integrate PGM-free catalysts in electrode optimization studies, as the thicker electrodes are expected to have a substantial impact on mass transport and water management.
- The proposed future work addresses further important issues such as polymer synthesis, characterization, and modeling. However, the impact on the membrane and the electrodes of more meaningful operating conditions (e.g., varying RH) and temperature conditions needs to be evaluated.
- Specific future work tasks were not given in the presentation. A qualitative list of remaining challenges and barriers were listed. Unfortunately, no property targets or fuel cell performance targets were listed. It is unclear whether the PI will continue to use ETFE as the electrode binder. It is unclear whether there is any compelling reason to use the PI's polymer membranes versus existing AEM films that are well described in the open literature. The technical target for future AEM/polymer stability studies is unclear. The cause of the gap between experimental and modeling results is unclear. The cause of the gap could include physical property data, electrode kinetic data, and/or insufficiently detailed models, but it unclear which is the cause.
- The future work mostly focuses on stability improvement (it is not clear how), diagnostics, and modeling to understand the effect of operating conditions. That is all good, but what is missing are the materials/designs for improved performance. Significant work must be done to show competitive performance with PEMFC systems—even without CO_2. All data shown were in oxygen—not air—with high loading Pt catalysts.

Project strengths:

- The work on water management has led to performance improvements.
- The project's strengths include access to promising materials, analytic methods, and expertise. The modeling support to understand fundamentals is very helpful. The transfer of knowledge from PEMFCs, such as applying the very good understanding of electrode preparation and characterization methods, is a strength. Support from industry partners such as 3M is also a strength.
- Polymer synthesis, membrane characterization, and fuel cell testing are the strengths and the heart of this project. It is great to see 3M involved.
- The attempts to address many of the major barriers represent a project strength. Other strengths include excellent collaborations, clear presentation of results, and not overselling or exaggerating results.
- The project addresses an important subject, that being the development and testing/evaluation of polymeric materials for the membrane and electrode binder in alkaline fuel cell MEAs and the modeling of MEA performance/behavior during fuel cell operation.
- This project contains a good balance of experimental and theoretical/modeling work, although it would be beneficial to see these better linked. The robustness of PF ionomer backbone and tether, as well as good water transport properties, provides a promising concept for continued development. Only the AEM did not ignore the effects of CO_2. The team should consider water management in the design and materials selection.

Project weaknesses:

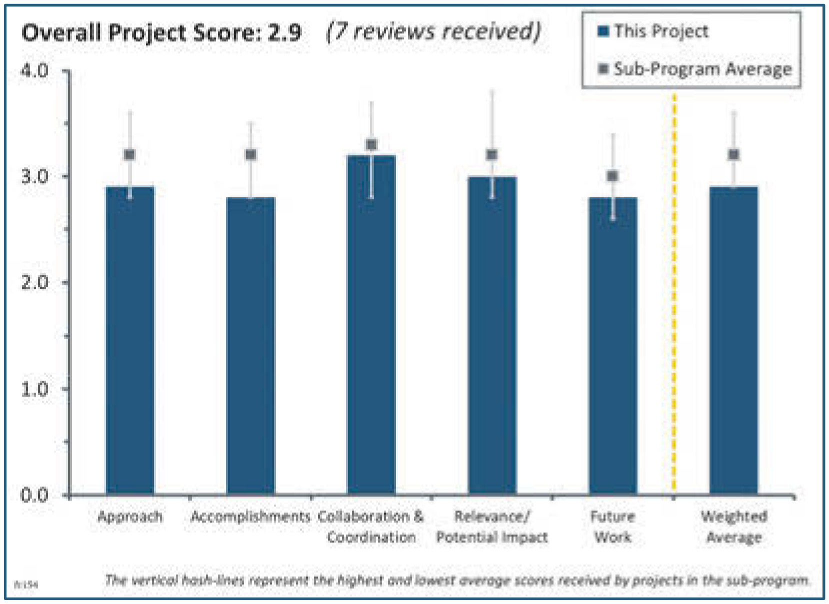
- The project team should devote some more effort to electrode development instead of simply relying on high catalyst loadings.
- The modeling has given some insights, but these insights seem to be premature until a good polymer is found to model.
- It is unclear how the modeling activity is driving development work. Project technical targets are defined to move the bar, but there is no clear definition of what would be required for original equipment manufacturers to consider implementing the technology. All testing is still taking place with oxygen, not air. All stability testing is in a steady state.
- The project continues to use alkylammonium cations that are degrading when the project team knows of more stable cationic groups.
- The PI's degradation test for Gen 2 and Gen 3 anion-exchange polymers is non-standard and not linked to conventional membrane/polymer durability tests in the literature. It is unclear how the PI's new polymers compare with AEM materials in the open literature. The performance of the PI's polymers as electrode binders in an alkaline fuel cell MEA is inferior to that of an established ETFE polymer (from Varcoe's group at the University of Surrey). The PI and the team have not presented an experimental plan to address this shortcoming. The PI indicated that the build-up of carbon dioxide in a recirculating hydrogen feed stream will be a significant problem during alkaline fuel cell operation, but no solution to this problem was indicated in the future work.
- The project cannot contribute to answering the question of whether the fundamental problems with AEMFCs (e.g., carbon dioxide, anode kinetics) can be overcome.

Recommendations for additions/deletions to project scope:

- The project team should set specific performance targets for the membrane and binder. The team should provide more information and results as to how the collaborators at CSM and UT are contributing to the project. The team should link the PI's durability test to the alkaline solution soaking tests that have been used by others. The PI must decide and explain whether the team will use ETFE or PF-AEM as the electrode binder in fuel cell MEAs.
- The team should keep working to further reduce ASR. The project should include validation of ex situ stability tests with in situ data. It is recommended that the project conduct performance testing in CO_2-free air and run stability tests longer than 15 hours. The project team should make sure to tie modeling work to materials development and consider the cost of concepts in materials/design selections.
- The team should investigate the stability of membranes and electrodes under more relevant dynamic conditions (temperature, RH changes) occurring during fuel cell operations. In addition, the impact of lower PGM loadings should be addressed in more detail.
- The team should focus on the Gen 3 polymer, interact with LANL group on side chains, and focus on stability, which is still a big question.
- The team should add ionomer development to the project scope. An AEM ionomer could be beneficial to all AEMFC developers.
- Some work with PGM-free catalysts in the water management work could be beneficial.

Project #FC-154: Fiscal Year 2016 Small Business Innovation Research (Phase II Release 1): Regenerative Fuel Cell System

Paul Matter; pH Matter LLC



Brief Summary of Project:

Fuel cells operated in a reversible manner are a promising potential energy storage solution, but high system cost is a major barrier. Development of a low-cost reversible fuel cell would be a key breakthrough for energy storage. This project, which builds on an earlier Phase I Small Business Innovation Research effort in platinum-group-metal (PGM)-free catalysis, aims to develop and demonstrate a reversible anion-exchange membrane (AEM) fuel cell that incorporates membrane electrode assemblies as regenerative stacks. System durability over 1000 cycles will be demonstrated, and economic analysis of the developed system for use as a grid energy storage technology will be performed.

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project has a clear objective of developing hydrogen and oxygen electrode catalysts for reversible AEM fuel cells, which is well supported by the technical approach. The project has successfully demonstrated 1000 cycles, which is well above the go/no-go decision point of 360 cycles.
- The project is directed at meeting the interim durability target for reversible AEM fuel cells and 1000 cycles at 42% round-trip efficiency by developing low-cost catalysts.
- The project aims to make inroads toward a more stable and cost-effective regenerative fuel cell system by using low-Pt and Pt-free electrodes.
- The approach is well-thought-out and does address many of the critical elements of a reversible system. However, this is quite a complicated "ask," as both galvanic and electrolytic processes are difficult to develop individually, let alone in a single device. The work presented identifies and highlights the areas that need to be perfected as well as what needs to be focused on in future projects. Some are related to the membrane and electrode dynamics, some are related to cell design and costs, and some are related to operating modes.
- The project team selected and combined cathode and anode catalysts as well as an AEM for a reversible fuel cell to improve cost and durability. However, the use of a platinum-free catalyst, which corrodes at high electrode potentials, and an AEM susceptible to carbon dioxide contamination limits the proposed system's capabilities.
- The approach, while ambitious, seems scoped adequately to address concerns about catalysts and cells. While it is dependent on ionomers and membranes supplied by others, for the size, it is acceptable. There is a concern, however, that perhaps the most significant issues are not being explored (e.g., the impact of potassium hydroxide [KOH] and pressurization). It would be beneficial to see the entire load cycle and its derivation, since it is not clear why the charge can be so much lower than discharge, depending on location and load profiles. This should further be used in the technoeconomic analysis to look at different profiles.

- The approach slide does not show technical terms. It is hard to know how pH Matter accomplishes such fuel cell and electrolysis data. The technical work scopes of pH Matter and Giner, Inc. (Giner) overlap. This project looks very challenging because there are not many resources available for reversible fuel cells.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project team identified platinum and platinum-free (COR-2, or CN_xP_y) catalysts. The team established the performance of the platinum-free catalyst for different compositions in a cell configuration. pH Matter demonstrated the durability of the platinum catalyst in a half-cell (no appreciable loss in activity). However, the platinum-free catalyst is not stable. The team demonstrated the operation with two different duty cycles and with a single cell and a three-cell stack. The team also demonstrated operation in a commercial electrolyzer with a four-cell stack and a potassium hydroxide electrolyte. Either a commercially available membrane or an unidentified membrane was used. An economic analysis was completed with a National Renewable Energy Laboratory (NREL) model.
- The team was able to develop 25 cm^2 cells that showed high durability for over 1000 cycles and was also able to simulate reversible cell operation for over 250 hours.
- The project has generated significant durability data in single cells as well as in three-cell stacks.
- The project completed the tasks for hydrogen electrode development, oxygen gas diffusion electrode (GDE) development, cell testing, stack testing, and economic modeling. The data on slide 7 shows better performance with a PtRu/C and HE-1 anode electrode than with Pt-Ni nanowires developed by the project partner. The fuel cell performance target was also met with a PtRu/C anode electrode (slide 9) and using hydrogen–oxygen rather than hydrogen–air. It is not clear whether the funding opportunity announcement (FOA) had specified and allowed oxygen as the cathode gas since there are system implications (oxygen storage in addition to hydrogen storage). It is not clear why the durability data in slides 10 and 11 are for low fuel cell voltages. The data in slide 12 indicates significant degradation in fuel cell mode. Slide 14 shows poorer performance in a four-cell stack (2.0 V cell voltage in electrolysis mode) compared to single-cell (<1.8 V cell voltage in electrolysis mode). Clearly, more work is needed in assembling stacks using the cells fabricated in this project. It is not clear what was accomplished in fiscal year (FY) 2018, since five slides (slides 7, 8, 9, 12, and 13) were duplicated from the FY 2017 poster.
- Overall, there were good accomplishments in terms of comparison of performance to baselines. The catalyst loadings, though, are somewhat high, and the baselines used appear to be much lower than state-of-the-art polymer electrolyte membrane systems. There is a concern and lack of clarity as to why KOH is required, and coupled with even the small amount of CO_2 produced, this creates concerns for a closed system that is being used. In addition, issues with parasitic currents could also be a concern with liquid electrolytes. The durability results are promising, although accelerated stress tests could be valuable. There is some question regarding the technical engineering analysis since it compares only a discrete fuel cell and electrolyzer with a unitized reversible stack, but the better comparison would be another technology that is electricity-in and electricity-out, such as a battery.
- The results point to technical areas that need to be further addressed. The accomplishments are positive, yet they are quite preliminary. The initial project targets are preliminary and will need to be reassessed if the technology is to reach a commercial state. More in-depth studies must be carried out in such areas as the membranes (about which, unfortunately, this work provides no information), catalysts, unknowns, and operating modes. These areas must be evaluated and better understood from a fundamental perspective. The cell hardware is also an unknown, and therefore it is difficult to comment on the impact the current design has on performance in this two-way process. The accomplishments must be re-reviewed once the goals and targets are modified.
- The progress of this project is disappointing. Slides 9 and 10 have basically the same data sets from slides 12 and 8 from the 2017 DOE Hydrogen and Fuel Cells Program Annual Merit Review (AMR). The previous year's AMR presentation stated the primary focus of this project was to develop electrode material. This year, the objective was changed to "demonstrating 1000 cycles..." Demonstrating over 1000 cycles is a good achievement. Three-cell-stack performance and cycling durability are also impressive.

However, it is unclear why fuel cell performance tested with the stack exhibited poor performance. There are many uncertainties about cell components regarding performance and cycling durability.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- The make-up of the team is quite good. It involves folks with knowledge of the critical aspects of any development effort, leading to the commercialization of a technology. It is anticipated that the input from the members will address some concerns: too early, not enough electrochemical and process engineering, and related mechanical engineering to date.
- There is strong interaction with Giner for testing commercial stack design and with NREL for low-PGM catalysts.
- The project has successful collaboration with an industrial partner and a national laboratory.
- There are three partner organizations: Giner, NREL, and Lockheed Martin. The contributions from Giner and NREL are clear. Although the interest in Lockheed Martin is clear, this organization has apparently not significantly contributed during this evaluation period.
- The team is well balanced, with relevant partners providing their expertise. The funding, however, seems to be perhaps insufficient for the partners to be fully engaged. Without a detailed breakdown, it is hard to ascertain.
- It is not clear how NREL's Pt-Ni nanowire contributes to cell performance and durability. Single-cell and stack testing by Giner provided some values, but the data looks different, as NREL uses different component materials and different test protocols. The role of Lockheed Martin on the project is not well defined.
- The FY 2018 poster does not have any slide identifying contributions from one of the partners.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is a very strategic project, especially with the renewed and growing interest in funding research of reversible fuel cells.
- The development of low-Pt- and non-Pt-based regenerative fuel cells is highly relevant to the Hydrogen and Fuel Cells Program.
- The project aligns well with the Hydrogen and Fuel Cells Program. The research on reversible fuel cells potentially gives much information to the fuel cell and electrolyzer mode. This project is more appropriate as a Fuel Cell Technologies Office (FCTO) FOA project rather than a Small Business Innovative Research project, since there are no standard materials available under high pH conditions.
- This project, especially the lower technology readiness level status, is in an early stage and is well aligned with current DOE objectives. If the technology is successfully developed and commercialized, the impact could be significant if the technology is deemed scalable and used in grid storage and power-to-gas applications. However, it has a long way to go.
- The project objectives are consistent with DOE's mission to develop fuel cell and hydrogen storage technologies. All the results included in the poster were obtained with the COR-2 cathode catalyst that was licensed from Ohio State University (not developed in this project) and the PtRu/C anode catalyst (presumably not developed in this project). The HE-1 anode catalyst also looks promising, but the source is unknown.
- The proposed regenerative fuel cell system has the potential to reduce cost and increase performance for energy storage. However, a carbon-based oxygen evolution and reduction catalyst in an AEM-based system is not expected to be durable because the high electrode potentials will corrode the platinum-free catalyst and the membrane will be contaminated by carbon dioxide in air.
- While the improvements are noted and show promise, there is an overall question regarding how reversible fuel cells are really part of FCTO and a good direction. The analysis, especially with different operating

regimes and conditions, does not address whether a single stack is better than two optimized stacks or other end uses for hydrogen or storage in batteries.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- This project touches only on the work that needs to be addressed to result in a commercial device. Membranes must be better understood; electrode composition, ionomers, and electrode structure and stability studies under a number of scenarios must be investigated. Scalability and the impact on realistic and practical applications based on engineering assessments of performance, reliability and, most importantly, economics must be evaluated, but it is too early. Substantially more detailed planning, testing, and development must be part of any future engineering and application activities.
- The team wisely identified the need to integrate with hydrogen economy and grow commercial partnerships as a future path for reversible fuel cells.
- The project ended in April 2018, and it appears that the project was not selected for Phase II extension. Therefore, very general future work is proposed.

Project strengths:

- The primary strength is that the team has touched upon the critical and most important aspects of the technology that need to be developed. The team knows what areas to continue to work on and what needs to be done. This implies the team has the know-how and resources to accomplish the next level of development.
- pH Matter did a good job in testing alkaline reversible fuel cells. The topic area is well aligned with DOE FCTO research subjects. This is a very challenging project because of the limited material availability. The project team's ability to demonstrate >1000 cycles with relatively stable performance is impressive.
- The project has a strong team with good progress on catalysts for AEM electrolysis and fuel cells under relatively benign but still significant conditions and loadings.
- The project team demonstrated 1000 cycles with a Pt-free catalyst. The collaboration with Giner brings demonstrated expertise in regenerative fuel cell systems.
- The project strength is its relevance to DOE FCTO.
- This project is highly collaborative and has an experienced team.

Project weaknesses:

- The project weakness is based solely on the expectations that commercialization of the technology is likely and economical. It is way too early to make any projections until the technical challenges are much better understood and the development path is clear, which is likely to take years. Unfortunately, the reviewer does not have detailed information on the critical components in this project and therefore cannot tell whether those components, individually, will be able to be commercialized as well (e.g., the membrane in this effort is still in a development stage, the catalysts are unknown, etc.).
- The project team had issues related to platinum-free and AEM durability. The other project weaknesses are several tests' use of KOH, which is not entirely relevant to an AEM technology because results may not be applicable or the test plan may ignore component integration (the existence of interfacial resistances); the small stack size, which could mask flow distribution and heat transfer problems between individual cells; and the apparent absence of integration for the Lockheed Martin team members.
- The current status of the technology project has an unrealistic stack lifetime necessary to provide high value. The project needs further materials research and stack design to increase the attractiveness of this technology for grid storage applications.
- The project has uncertainties about the use and function of KOH that may limit the applicability or knowledge.
- The project has not made much progress since last year. The poor cell performance in the electrolyzer mode needed to be identified before cell testing. The material availability for this project is a substantial

problem to demonstrating good cell performance. There is not a knowledge-learning process from this project. Overall, the partnership is weak.

Recommendations for additions/deletions to project scope:

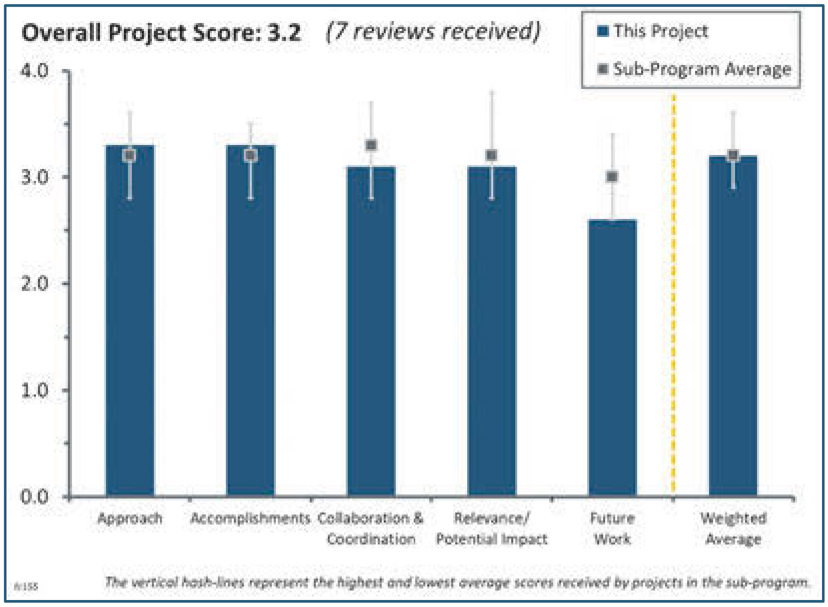
- The project team needs to find the alkaline membrane, ionomer, and catalyst supply unless pH Matter has some potential materials to use. Also, the team needs to show a clear pathway of how this technology can ever be commercialized. Last, the team needs better-defined short-term and long-term targets.
- The project team should investigate what the economics and engineering requirements are for the storage application and then look at the technology under development. Additionally, the team should add in-depth analysis tasks for the membranes, electrodes, process engineering, cell design, and of course, much longer testing, cycling, start–stops, reliability, and costs (including stack life). It does not make sense to compare costs to automotive components, as the lifetime and performance expectations are totally different. The team should reassess such evaluations.

Project #FC-155: Novel Ionomers and Electrode Structures for Improved Polymer Electrolyte Membrane Fuel Cell Electrode Performance at Low-Platinum-Group-Metal Loadings

Andrew Haug; 3M

Brief Summary of Project:

The objective of this project is to develop novel ionomers and electrode structures to improve polymer electrolyte membrane (PEM) fuel cell performance and durability. The focus of the ionomer development will be on combining high proton conductivity with improved oxygen transport. The project also seeks to understand and optimize novel cathodes that utilize nanostructured thin film (NSTF) catalysts in powder form. These powder catalysts will be integrated with the ionomers to develop an advanced cathode of high activity and durability. State-of-the-art novel characterization and modeling techniques will be used to guide these development efforts.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project focuses on overcoming cathode transport limitation using dispersed NSTF and novel ionomers. The project clearly addresses the following key barriers identified by the Hydrogen and Fuel Cells Program (the Program): cost, durability, performance, and operational robustness. The targets set for the project with respect to the catalyst, support, and membrane electrode assembly (MEA) are clearly laid out and meet or exceed the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP) targets. The approach of dispersing NSTF has the potential to change both the NSTF paradigm (lacks an ionomer, prone to flooding electrodes), while also changing conventional Pt/C-based electrodes by having supported catalysts of unique aspect ratios. The use of novel ionomers is welcomed, as well, which can move levers around O_2 permeability and H+ transports (thereby reducing the ionomer content). It is not clear why particular ionomers (perfluoroimides) and multi-acid side chains (MASCs) were chosen, why it is assumed they would move properties in the desired direction, and how they are different from the 3M725 and 825 chemistries.
- In principle, NSTF could be an ideal extended-surface object for incorporation into a dispersed catalyst layer. The idea has existed for a while, and it is good to see this project funded. Hopefully, specific activity is much higher than for nanoparticles. The project designs the approach by focusing on what happens at the ionomer–platinum interface, which is reflected in the measurements of oxygen permeation and proton conduction through ionomer. These characteristics are also mentioned in the two go/no-go decision points. However, not much is mentioned about the catalyst layer design as it pertains to Fickian mass transport losses; it would be easy to imagine a very compressed layer of NSTF objects with little porosity. The project is more proactive than past NSTF projects in addressing conditioning and robustness. This needs to be encouraged further.

- The project approach involves two main thrusts: the development of improved electrode ionomers with higher oxygen permeability and higher proton conductivity, and the development of new electrode structures based on dispersed NSTF powder. Both thrusts are highly relevant and hold promise for enabling improved fuel cell performance and durability.
- NSTF continues to offer promise for high activity and durability. This project is looking at novel ionomers in electrodes and using NSTF in a dispersed nature; these approaches are of value. The synergy between the two approaches, if it exists, is not clear.
- The approach is very well planned to demonstrate relevant technical targets at the end of the project.
- Modifications to the basic ionomer are important to improving performance at low loadings; however, it is not clear how/why an imide-based functionality will lead to higher permeability. Ever since NSTF first came out, people have been asking 3M to try it as a powder, so it is interesting to see them do so. However, 3M does not report on whether this is at all a cost-competitive method.
- The idea of enhancing performance by removing the barrier to oxygen diffusion is based on an ideal situation of NSTF catalyst layers and well-defined ionomer coatings. After mixing and coating electrodes and deposition, the actual structure is far from ideal, making this starting point uncertain.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Excellent progress has been made for the project’s end goals and targets. All milestones and go/no-go points to date have been met or are on track, and progress has been made. This is indicated by clear metrics summarized in the table on page 5.
- The project has produced a significant amount of data regarding novel ionomer development, characterization, and implementation in fuel cells.
- Advances in Tasks 1 and 2 have been meaningful. Studying the importance of deposition thickness and evaluating several different catalysts and electrode ionomers provided value. The performance and durability obtained have shown promise. Transition metal leaching issues seem more severe than would have been expected.
- A significant amount of work has been achieved in sufficient detail for the synthesis and characterization of the electrodes. Through these results, progress is clearly visible, albeit not always in correlation with the expected outcome.
- The ionomer development work has been highly successful in terms of meeting and exceeding goals and showing substantial improvement in both oxygen permeability as well as proton conductivity versus the baseline 825 equivalent weight (EW) ionomer. The incorporation of ionomer thin film studies at Lawrence Berkeley National Laboratory (LBNL) has been helpful in building an understanding of the reasons the novel ionomers show improved permeability. The ionomer conductivity measurements are useful for direct quantification as well. Durability of the ionomers, and especially possible catalyst poisoning due to ionomer degradation products, is the largest concern. Some data were shown on the electrochemical surface area (ECSA) change during the catalyst accelerated stress test (AST) for perfluorosulfonic acid (PFSA) versus imide ionomer, but it would be good to see more data about changes in mass activity and high-current performance after the AST as well. Though high-level numbers were shown in the summary table (which indicated potential problems with durability), a more detailed discussion and a direct durability comparison with baseline ionomers should be included next year. The dispersed NSTF work is a promising approach, but so far, the encouraging results with the 10Pt/10α NSTF have not enabled high performance at high current. Durability is also a concern with this material. While the ECSA loss during the catalyst AST was shown to be low, the loss in performance at 0.8 A/cm^2 appears to be over 100 mV, far exceeding the DOE target of 30 mV.
- There is nice progress toward DOE and internal targets. It is uncertain how the team is addressing or characterizing the ionomer stability other than through MEA aging performance. The ionomer work is substantial, as the team continues to lower EW while maintaining viability. Just reducing the break-in period for NSTFs has made this work worthwhile.
- The presentation slides appear to contain numerous errors, including a few places where it is unclear whether the liner loading is meant to be expressed in micrograms per square centimeter or milligrams per

square centimeter. The DOE-supported AST data contains an error in experimental design. MYRDDP Table P.2 shows that the current density at which performance losses are to be measured is 1.5 A/cm^2, not 0.8 A/cm^2. The investigators should take notice. It is also unclear what is meant by "Meets metal AST targets." The performance loss at 0.8 A/cm^2 for the electrocatalyst AST (for 10Pt/10α) is approximately 100 mV, not <30 mV, as targeted by the test. It appears that at 0.125 g/kW, the 10Pt/10α sample is at Q/ΔT = 2.36 kW/K (0.61 V at 80ºC). This should be noted as being a higher Q/ΔT than that at which the g/kW metric should be reported. Robustness testing has passed the targets, but it appears this may need to be repeated for most stable NSTF (with α). It is good to see a focus on conditioning time noted in the technical backup slides. This needs to be repeated for the most stable NSTF.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- This is mostly a 3M project, but that makes sense, given that 3M is the most appropriate organization to perform the work and has the capabilities required for most of the key tasks. The limited interaction with Tufts University and Michigan Technological University (MTU) appear helpful, if not entirely critical. The Fuel Cell Consortium for Performance and Durability (FC-PAD) interactions with Oak Ridge National Laboratory for microscopy, and LBNL for ionomer thin film studies, also appear helpful.
- Collaboration with two academic institutions and capable FC-PAD laboratories is a big advantage for the successful completion of the project. So far, contribution from the partners is very good.
- The team members, plus FC-PAD, are all excellent and appropriate. A clear connection with FC-PAD laboratories was highlighted in the work presented.
- There are no doubts about collaboration, although progress in making a (predictive) model seems slow and unconnected.
- This is clearly a 3M-dominated effort; however, there is nothing wrong with that if they have the majority of the tools that they need. The team could aid in the presentation if the slides where the collaborators provided the data show this. After slide 1, only the 3M logo is seen on each page, making one think that all the work was done by 3M; if this is not true, that particular detail should be changed.
- It seems a bit unclear how the collaboration with MTU will contribute to meeting the project goals. The measurement of the ionomer contact angle is interesting, but the project leaves uncertain what the desired contact angle is. Advances in the project appear to be occurring without a validated model. The model is being developed in parallel, but it appears the project could continue without it. Tufts University appears to make some contribution on Task 1 with ionomer conductivity measurements. FC-PAD provided some interesting images to help explain ECSA loss at different liner loadings. FC-PAD could probably be used in more areas of the project.
- The extent of collaboration is not clear from the presentation. It appears as if the work is siloed off. Minimal work from Tufts University is shown, even though the sole publications appear to be authored and funded from that institution. It is unclear how FC-PAD work is being integrated and what the MTU work/ impact is. The goals were written as though advanced characterization and modeling would be used to guide experiments.

Question 4: Relevance/potential impact

This project was rated **3.1** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Work on improving transport and performance in electrodes is extremely relevant to Program goals. There is some reason for concern that the addition of ionomer to NSTF-based electrodes will cause new transport barriers associated with ionomer thin films, but given the known breaking and robustness issues with conventional NSTF, this is a highly logical approach to adapting NSTF, making it relevant for automotive applications.

- Lower EW ionomers with higher permeability will always aid in performance. Extending the promise of NSTF over more operating conditions with less break-in is also helpful and is seen in the good work toward making power metrics.
- The project is addressing important barriers such as cost, durability, and performance through the development of novel ionomers and is integrating them with powdered NSTF catalyst in fuel cell MEAs.
- The project is looking to take on the highest concerns of DOE targets and commercialization. Increasing mass activity and enabling improved water management remain challenges, but the NSTF approach has shown promise in addressing these challenges, and progress in the last year has been good. Novel ionomers also offer potential advantages in performance, particularly in local transport resistance. The results shown suggest improvements may be made. More durability work on the ionomers and addressing the transition metal leaching are both areas that need further effort.
- The project has the potential to make an impact on MYRDDP goals, technically, as shown by the support and metal stabilities. Some of the ionomer results appear to be promising. The total cost of the dispersed NSTF, even at low loadings, is not really addressed at all. It would be beneficial to have some sort of transportability engineering analysis. As pointed out last year, higher performance would be desirable, as would the reporting of $Q/\Delta T$.
- The NSTF catalyst particles have exceptionally well-defined properties, which are lost to some degree if the layers are not equally well defined to provide clear-cut data to build the model, proving that the initial assumptions are indeed correct. If it is proven that the oxygen permeation is significant and can be reduced, this would be great learning that can be applied to all. However, if this limitation is only relevant in situations with solar energy factors (SEF) <10, and SEF >100 electrodes provide better performance and do not have this problem as a bottleneck, then the reason to study this catalyst's layers is valuable only as a model system.
- Despite the possibility that dispersed NSTF could be a very interesting extended-surface catalyst, the relevance slide seems to present some logical inconsistencies. Literature data are shown that clearly indicate that NSTF avoids the trend of ionomer-containing catalyst layers decreasing in performance at low roughness factor. However, this project wishes to disperse NSTF into a catalyst layer with an ionomer. Unless there is some enhancement in the roughness factor (without increasing loading), this may simply cause NSTF to fall into the same tradeoffs familiar to dispersed catalysts. Targets for performance, robustness, and various ASTs well represent the metrics needed to understand the technology's promise.

Question 5: Proposed future work

This project was rated **2.6** for its proposed future work.

- The proposed future work will help overcome some of the barriers in achieving higher fuel cell performance.
- The future work could be more detailed, and durability should be more thoroughly addressed, but overall, the work appears appropriate.
- The team continues to innovate and try new ionomers, which is good, but it would be helpful if there were an underlying fundamental approach. The majority of gas permeability is in the water phase, so changes in the backbone are unlikely to lead to big changes in gas permeability. The team is trying to reduce the equivalent number of NSTF layers required, but it is difficult to judge whether 10 layers is the right number. It is unclear what the team is driving toward. The team members are, no doubt, doing the economic analysis, but it would be good if they shared what they believe is the final acceptable endpoint, whether it is 5 or 10.
- NSTF alloy integration is considered "critical"; however, it might be wise to consider whether durability, high-current performance, and conditioning are more critical. Certainly, the alloy would help with drive cycle efficiency, but cost and durability, not efficiency, are the major barriers to commercialization. Most of the future work focuses on transition metals. "TMI" as an acronym is not well defined. Some of the project slides need to do a better job of spelling out acronyms and other internal project terminology. Some of the presentation is written in code.
- It is hard to follow some of the details and future work activities, especially when looking at the project holistically. Use of alloyed catalysts seems to be desirable to achieve goals; however, the goals were to use advanced ionomers to do that, not new catalysts, and catalyst processing. It is unclear how FC-PAD

capabilities and knowledge will be leveraged in the future. It is unclear how the new ionomer-swelling issue will be addressed. If the catalyst layer swells, it will negatively affect oxygen transport and water removal, not to mention structural stability.
- Many activities are summarized as optimization, while a degree of unforeseen issues is clouding the structured approach. The anticipated model as a predictive tool may not be finished in time to help identify the right direction to obtain best-in-class results quickly.
- Future work largely continues the approach applied to date, in some cases combining the efforts from the specific tasks. It is not clear how, or if, there will be synergistic advantages (or potentially disadvantages) in combining the NSTF approach with different ionomers.

Project strengths:

- The concept of dispersing NSTF objects has long been sought as a possible high-specific-activity catalyst with water management advantages. It is good to see the concept being developed. The project has placed greater emphasis on conditioning and robustness and has the resources at 3M for industrial scale-up. 3M is very experienced in fuel cell catalyst development.
- The ingredients of this project are strong, both in terms of the catalyst and ionomer, as well as the tools for characterization and presentation of results. There is high potential, provided the initial assumptions that oxygen permeation causes great resistance in this situation (SEF <40) are true.
- The main strength of the project lies in the potential impact of a dispersed NSTF-based catalyst layer utilizing a game-changing ionomer. There is a potential overall impact from leveraging collaborations and FC-PAD.
- The project contains best-in-class performance and the best ongoing work being done in the field on pushing ionomers. There is good durability being shown on NSTF catalysts; making a powder is addressing some of the project's shortcomings.
- This project's strengths are a well-thought-out technical approach and the execution of proposed research and collaboration with academic partners, as well as with FC-PAD consortium member laboratories.
- Dispersed NSTF and alternate electrode ionomers are both highly relevant research topics. The team and unique materials are excellent.
- 3M has excellent capabilities for developing novel ionomers and novel electrode structures based on NSTF.

Project weaknesses:

- Work pertaining to layer development will likely stay confidential and will be difficult for others to reproduce. The project may place too much emphasis on alloys versus making sure the Pt/α system achieves durability, robustness, and high-current-density performance targets. The presentation slides need to be more refined. The project is somewhat depicted in code, with easily identifiable mistakes apparent. Some of the material appears to have been assembled in a hurry. Modeling work needs to be better incorporated into the tasks necessary to meet targets.
- There does not seem to be effective collaboration between FC-PAD and its prime contractor and subcontractors. The approach seems to be to do whatever it takes to meet targets without a well-defined procedure. There is a lack of use of modeling and advanced characterization to accelerate innovation or understanding.
- The link between NSTF and novel electrode ionomers is not clear. It seems unlikely that there is a synergistic benefit to looking at both issues in the same project, although both merit investigation individually.
- Within the constraints of the mentioned catalyst and ionomers, the project does not necessarily provide a good catalyst layer design for the PEM. The value of a clear model for a defined system could be diminished if the results do not show correlations in the results because of many other factors influencing performance.
- The slides were presented well, but they are hard to follow when reviewing after the presentation because of poorly labeled figures and undefined non-standard acronyms.
- It would be good to see the philosophy of increasing permeability. The reviewer cannot judge whether the NSTF powder can be made economically.
- The project needs a cost analysis of the novel ionomers.

Recommendations for additions/deletions to project scope:

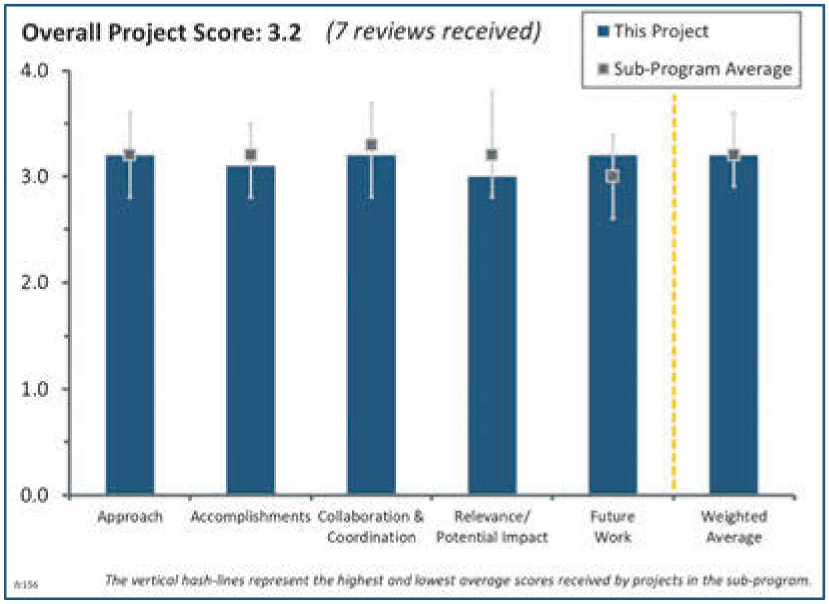
- An added emphasis on robustness and conditioning, especially for best-in-class materials, is always welcome. Robustness and conditioning represent some of the issues that have prevented commercial systems from using NSTF. Catalyst layer thicknesses were not clearly shown in the presentation. It would be interesting to see an elemental mapping of catalyst layers to see how well the ionomer is distributed and whether there are performance improvement opportunities.
- Slight modifications are necessary to cell testing and the reporting of results in areas such as impact of the ionomer-to-carbon (I/C) ratio on fuel cell performance and durability, as well as the impact of the I/C ratio on the electrochemically active surface area. Overall, this is a very solid approach with good results.
- Results (both positive and negative) should be clearly linked to the factors responsible, thus creating insight, in addition to the large amount of data presented.
- It would be good to see some work in characterizing ionomer durability. The wisdom of introducing Ru is questionable if the project team cannot show stability first.
- The project should add full MEAs using low-loaded Pt/C and in-project developed ionomers. It is unclear whether this alleviates the localized mass transport issue.

Project #FC-156: Durable High-Power Membrane Electrode Assemblies with Low Platinum Loading

Swami Kumaraguru; General Motors

Brief Summary of Project:

This project seeks to improve the durability of a state-of-the-art (SOA) membrane electrode assembly (MEA) by identifying and reducing the stress factors affecting electrode and membrane life. Project tasks include (1) MEA optimization of a low-loaded electrode through down-selection and integration of MEA components, (2) durability studies of the developed MEA, and (3) development of a predictive model for degradation in different operating conditions.



Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach includes a balance of fundamental materials studies (mostly at the Fuel Cell Consortium for Performance and Durability [FC-PAD] laboratories) and an MEA evaluation of materials, with results fed to models for prediction of durability. The project is evaluating SOA materials and determining how best to combine the materials into MEAs, as well as how to operate the MEAs for maximum durability. The project is not developing new materials, though it is using cutting-edge materials developed outside the project.
- The project is addressing several key issues regarding the performance and durability of non-platinum-group-metal (non-PGM) catalysts for MEAs. The outline of tasks, detailing those initiated and also in progress, is good.
- The project contains a structured approach and a clear definition of the phases with a goal to define benign operating conditions.
- The project focuses on the main issues relevant for fuel cell electric vehicle (FCEV) commercialization. General Motors (GM) brings real-world experience, SOA materials, and integration capability. The only downside to the project is how many different areas are being taken on within. This may be less of an issue because perhaps GM would take on these issues anyway, with the overall impact being a higher cost-share contribution for the U.S. Department of Energy (DOE)-funded effort.
- Overall, the project's approach is good. The project appears to be primarily aimed at identifying operational factors that induce decay with SOA MEAs and identifying operating modes that minimize decay. The use of modeling and characterization is necessary and warranted. One aspect of the approach that could be improved is the incorporation of durability testing earlier in the project and with more MEA types. It appears that the approach during the first year was to identify the MEAs with the overall best performance. It is unclear whether the degradation modes and benign operating conditions identified for this "best performance" MEA will be applicable to a wider range of materials than the GM-specific material sets.
- To achieve DOE 2020 performance and durability goals with SOA MEAs, the approach is well-thought-out. However, a good deal of work on electrode and membrane durability has already been done by previous DOE-funded projects; few models have been developed, so it is difficult to understand the novelty in the approach. Also, some of the stress factors in the MEA mentioned in the study are dependent on how

the MEA is manufactured. Electrode cracks can be controlled by the ink recipe and slow drying, and localized stress caused by fibers from the gas diffusion layer (GDL) can be easily eliminated by prepressing the GDL before the MEA and/or electrode assembly; so the model can be generalized for various MEAs by the catalyst-coated membrane, the gas diffusion electrode approach, or a combination of the two, as in the Mirai MEA.

- The approach is generally good, but some improvements are possible. The approach should not be to define benign operating conditions but rather to map out the effect of operating conditions. Original equipment manufacturers (OEMs) can then determine the tradeoffs with the system and the MEA design. Considerable and useful effort was expended to down-select the cathode catalyst layer components. The work was conducted systematically, and useful correlations were obtained. It is not clear what is being referred to in terms of "higher than expected" membrane degradation. It would be valuable to also consider durability aspects for the cathode design. There is a good combination of experimental studies and characterization. The highly accelerated stress test (HAST) work on membranes is interesting and should result in an improved understanding of in situ mechanisms. The fundamental model of mechanical/chemical stress in the membrane will be useful, and an appropriate set of variables has been established, including interactions with the GDL. While the experimental basis for the model is well mapped out, the theoretical basis is not clear.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- A high-performing MEA was achieved using conventional approaches via the systematic testing of key materials representing a range of parameters. HAST and shorts approaches for the membrane were developed, which will be useful. There was a nice correlation found for proton transport resistance versus carbon macropore surface area. The characterization of ink structures with different solvent types was useful. There is good characterization of Ce removal from the MEA. The result in the ex situ jig, showing Ce movement by convection, was interesting.
- Excellent progress has been made in preparing and characterizing prototype MEAs with selected catalysts.
- The project is making steady progress in evaluating materials and has produced an SOA MEA with impressive performance levels. The new catalyst supports being incorporated in this project are providing excellent performance and helping to build an understanding of the relevant support parameters that determine oxygen and proton transport resistances, although, in this area, there seems to be much overlap with the GM catalyst project. The project seems to be very helpful in enabling GM to screen materials for use in the company's own MEA development work, but so far, there does not seem to be much learning that could help the community as a whole.
- The project has made good progress in demonstrating a low-loading MEA and meeting DOE loading targets, which also meets the rated power target (but not the Q/dT target at 150 kPa pressures). Additionally, the project has accomplished a good deal of the characterization of the multitude of catalysts, electrodes, inks, and membranes. Development of the Ce migration characterization looks to be a significant accomplishment. It is unclear how this multitude of data at the component level (e.g., ink viscosity) will be utilized toward development of the durability model.
- GM has been able to screen a number of SOA membranes, catalysts, and ionomers to produce the highest-performing MEAs possible. The team has shown good results in terms of achieving rated power performance. These results are clearly relevant for accelerating commercialization. Other efforts are fairly disconnected and, in various cases, have resulted either in meaningful results (e.g., Task 1: relating carbon support type to proton transport resistance, the impact of equivalent weight, etc.) or cases in which the impact of these studies is still undetermined (Task 5: X-ray computed tomography [XCT] for shorting, Ce migration, etc.).
- In comparison with the milestones and tasks listed, the progress and accomplishments are good. However, some of the work done here is already well reported in literature (e.g., the effect of water–alcohol ratio on catalyst–ionomer interaction), so there is no need to "reinvent the wheel." Instead, learnings from published work can be adopted.

- Much work has gone into defining a good baseline MEA using the best selection of materials. Progress was made in improving processes, performance, and the evaluation of defects in the MEA. Very little is shown on the durability, and there are no projections on more benign operating conditions (yet) at this stage.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- GM really needs only modest support to execute a work scope like this. The team has leveraged FC-PAD effectively and has small, well-defined roles at the University of Texas at Austin (UT Austin) and Giner, Inc.
- It appears that greater contributions were obtained from national laboratory partners during the past year. This project has a good delegation of assignments for both characterizations and testing.
- Significant collaboration is planned, drawing on key strengths from other groups.
- The project's collaboration appears appropriate and is directly relevant.
- The project is well coordinated with partners and collaborators. Most of the work is performed at GM, but the interaction with Lawrence Berkeley National Laboratory and Argonne National Laboratory for ionomer properties characterization is useful. The extent of interaction with the FC-PAD laboratories so far appears limited because of the lack of a non-disclosure agreement.
- Collaboration with FC-PAD seems very strong and easy to understand, but the roles of UT Austin and Giner, Inc., look very small in the project. GM, as the principal investigator of the project, is doing almost all the work.
- There are no discrepancies or misalignments in the presented PDF.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The relevance for this project is generally high as it pertains to durability in a high-performing MEA design. However, there are concerns about defining a set of operating conditions specific to one MEA type. This will provide one path forward to demonstrate an MEA that meets both performance and durability; however, it may not provide the best overall tradeoff between MEA performance/durability and system design. The approach will also provide useful information that will assist others in design and durability understanding.
- The development and implementation of SOA MEAs is highly relevant to achieving DOE targets and advancing fuel cell commercialization. The topics included go beyond the SOA MEA performance; both Ce and shorting are important and need to be understood. How much impact will result from this project and what will be learned are still to be determined.
- The project is directly addressing key cost, performance, and durability barriers with SOA materials, and it appears that there is a good probability of achieving many DOE targets. However, the impact may be only to the OEM prime contractor and not the industry as a whole, unless additional information is disclosed regarding specific material sets used. It is suspected that this disclosure may not occur, as it may be highly valuable to the OEM for potential future products.
- The project is helping to build an understanding of existing materials, determining how best to combine SOA materials into high-performance and durable MEAs and developing operating strategies to improve durability. This is useful work, but the development of improved operating strategies is highly application-specific; therefore, it is less relevant to the overall DOE Hydrogen and Fuel Cells Program (the Program) compared with new materials development, which can help all applications.
- This project is relevant to DOE's 2020 performance and durability goals, but it is unclear how the developed model can be utilized for other FC-PAD projects or future DOE projects to develop SOA MEAs.
- There is value in making a better MEA and sharing the lessons learned, but perhaps the true benign conditions for operation are obvious. Only in combination with a system running at rated power density or in specific off-spec conditions can major degradation be expected. This is more of a systems control area

for optimization, eliminating extreme conditions. It may prove difficult to identify specifically damaging elements within incumbent fuel cell operation conditions that benefit a greater audience.
- While reversible MEAs have potential applications in various applications, the presenter did not address the issues with meeting DOE targets for FCEV power systems. The team needs to explicitly state the most relevant and critical factors that are being addressed regarding the development of commercially viable devices.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- A good plan was presented for the next phase of work. It is imperative to conduct the durability measurements and also support the post-operational materials characterization assessment on degradation processes.
- The proposed future work aligns directly with the project plan, with an increased focus on durability studies and degradation mechanisms via physical characterization and modeling.
- The future work is appropriate for the project goals and objectives. The work has been carefully and thoughtfully planned.
- The plan forward is appropriate.
- The proposed future work looks good and is aligned with project milestones, but the roles of other team members are unclear.
- The project team has excellent intentions, but the net may be cast with too wide a scope to capture all the points mentioned. It is expected that only a few chemical/mechanical stress factors can be investigated.
- The layout of the project over the three different budget periods does not seem to be the most effective for building on advances throughout the project. While the focus on performance in budget period 1 (BP 1) leads in well to BP 2 and durability, the value to the community in developing models in BP 3, and how it connects, is not as clear. It seems it would have been better had this effort been integrated into the earlier efforts so that learning could be applied to the project as it was being executed/performed. All proposed tasks are either good or, at minimum, reasonable.

Project strengths:

- The excellent component and MEA integration and testing capabilities at GM are a significant strength. The access to a broad range of SOA materials is also a major strength since most institutions cannot get access to the best materials.
- This project contains very systematic studies and provides an approach to achieving MEA targets for both performance and durability in the system, although it may place significant constraints on the system. There are good characterization approaches and planned model outcomes.
- The project team has access to SOA materials with good prospects for achieving project performance targets and recognized expertise in component integration into leading MEAs.
- Team strength, materials access, and considerations for system tradeoffs/costs are all strengths of this project. High-performing samples that are relevant for commercial vehicles are also a strength.
- There is a good structured approach that can capture and structure results to provide good learning, coming full circle to operating conditions.
- With GM (industry) as the project lead, along with FC-PAD collaboration, good and relevant results can be expected.
- This is a good, experienced team with members who have performed credibly so far on the tasks identified for this project.

Project weaknesses:

- The total project structure has many activities, too wide a scope, and a long feedback loop, which, in effect, could incorporate all possible activities elsewhere in the process. In this presentation, only the first phase is supported, defining and optimizing the MEA, and no durability or cycling has been attempted. The

reviewer slides state that first, variations and control variables need to be identified to limit the number of relevant options to explore.
- Apparently, the broad scope of activities within this project has delayed converging on an optimized membrane configuration for performance characterization and conducting the durability assessments. It appears that much of the technology is being considered proprietary, which seems to be hampering full sharing of properties with partners charged with the supporting materials studies.
- The focus on tailoring operating conditions, rather than materials properties, to obtain good durability is a slight weakness because of the non-universality of this approach. Within the context of the Program, materials solutions should always be favored over systems solutions.
- The project's relevance to the general community may be low because of use of proprietary materials that may not be otherwise accessible. There are insufficient first-year efforts on the down-selection of durable materials (i.e., down-selection appears to be based on performance only).
- This project may be too specific to one MEA type and may place significant constraints on the system. There is a lack of clarity on model approaches.
- This project lacks novelty in the approach and looks like a consolidation of previous works in an attempt to make it more meaningful.
- The modeling effort could be better integrated into the performance and durability efforts.

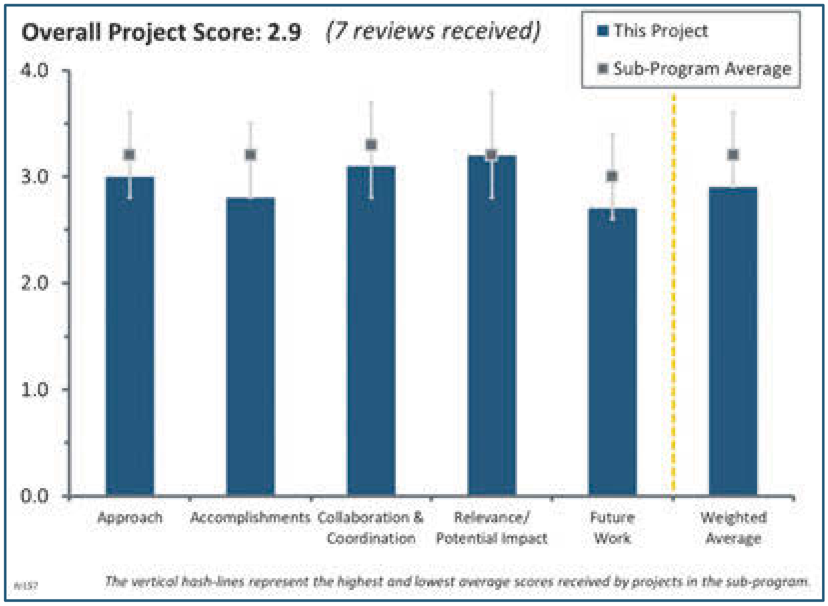
Recommendations for additions/deletions to project scope:

- Overall, the stated plan for future work is strong and should be followed. Emphasis should be focused on identification via device and the materials aspects of degradation processes. However, at the current rate of progress, it seems that objectives related to durability will not be achieved.
- The project has good work and an interesting presentation. It would be good to see similar momentum and direction for the durability assessment going forward. The team must be wary of an anticlimactic ending in the final project conclusions, as operating conditions were not changed from the status quo.
- In addition to SOA proprietary materials, the project should include generally available reference materials (e.g., Pt/Vulcan catalyst) into development and characterization plans, allowing for dissemination of all results.
- The project's scope is appropriate and useful. However, an understanding of the design tradeoffs between durable and high-performing designs would be useful as well, if there is room in the scope for any addition of work.
- The project is extremely broad. It may be better to narrow it down to achieve more depth.
- It is unclear how the developed study/model can be used by other DOE projects.

Project #FC-157: High-Performance Polymer Electrolyte Fuel Cell Electrode Structures

Mike Perry; United Technologies Research Center

Brief Summary of Project:



The objective of this project is to improve the fundamental understanding of transport limitations in state-of-the-art (SOA) membrane electrode assemblies (MEAs) for polymer electrolyte membrane fuel cells and use this knowledge to develop and demonstrate high-performance MEAs with ultra-low catalyst loadings (ULCLs). Transport losses are a major barrier with ULCLs, but fundamental understanding of those losses is currently lacking. To gain better understanding of the nature of these losses in cathode catalyst layers, a detailed microstructure model of the cathode catalyst layer will be developed. This improved knowledge will then be utilized to develop improved MEAs that meet the U.S. Department of Energy's performance targets.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project identifies that mass-transport limitations in the electrode are a critical barrier and focuses efforts toward understanding the cause of the transport limitations. The project's approach is logical and extends current modeling approaches to develop a hierarchical model looking at three different length scales: that of the electrode, the agglomerate, and the catalyst particle. The use of traditional- and non-traditional-type catalysts will test the model's capabilities. The project is integrated with other Fuel Cell Consortium for Performance and Durability (FC-PAD) efforts. Key to the effort is accurate description, characterization, and control of the agglomerate size. More information on how this will be done would be beneficial.
- The relatively simple approach has already demonstrated correlation with results and validated itself in comparison to published data.
- The design of the approach and organization of the team and resources are well aligned to address the specified problem. Iteration throughout the process will help to refine the model and increase the chances of success. What is limiting is the apparent disconnect between the model development and analysis, and the catalyst development, namely, the non-conventional catalysts. The key accomplishment of the model is the integration of spherical diffusion around the catalyst particles. This is seemingly not relevant for the thin film catalysts tested in this project.
- Modeling projects are always difficult to judge without doing an extreme deep dive into assumptions and methods. The team's data fits well but, as the presentation speaker said, all models are wrong; this approach will work only if the underlying approach is accurate. In that regard, the project team is not looking at work that General Motors (GM) is doing and testing their assumptions, or modifying a model that may have non-ionomer ionic transport. It is the use of models and fitting that has clearly demonstrated

the unexplained high transport resistance, and now some solutions for it, so it is important to have competing models out there.

- The project is focused on understanding mass-transport losses observed at high current densities (HCDs) for electrodes with low Pt loading through modeling and experimental validation. There are some flaws in the modeling approach, as it assumes a one-size Pt/C agglomerate for catalyst layers with a given Pt loading.
- The approach consists of developing the realistic microstructure model to understand mass-transport losses, which seems very helpful, but the integration of the effect of ink mixing, the ink recipe (water–alcohol ratio, etc.), and MEA fabrication (drying speed and time, etc.) that affects the catalyst layer structure is not very clear.
- The approach of this project relies on having the ability to construct a structure and a fundamentals-based model, identifying the flaw, and then constructing an electrode structure that alleviates the HCD performance loss. It is an idealistic approach that has been tried by other groups in the past seven years and has failed.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The modeling efforts have made good progress and have been able to reproduce performance under a variety of conditions. The model reproduces performance losses at low catalyst loadings without having to alter ionomer properties from the bulk properties. The thin film catalysts have been successfully integrated into an MEA. The modeling effort has identified agglomerate size and ionomer equivalent weight (EW) as the two important characteristics to change to improve performance. The performance of the thin film catalysts needs to improve. The model has been validated with both literature results and results at the United Technologies Research Center (UTRC). Experimental work has been slowed by construction at UTRC.
- Progress has been made toward understanding the nature of mass-transport limitations in catalyst layers with low Pt loadings. The proposed hierarchical model qualitatively describes trends in changing transport resistance with Pt loading. Furthermore, the model validation shows that there is no agreement between the experimental results obtained for transport resistance versus Pt weight percent. There is no good agreement between the experimental data for transport resistance versus Pt loading and modeling results, as well. The agreement in the experimental results for Ion Power, Inc.'s (Ion Power's) low-loaded Pt/C MEAs was good and obtained using the "limited number of fitting parameters," which usually implies that there were some problems with the physical justification of the model.
- It is hard to judge the accomplishments of this project without many details on how the model is developed, as well as the efforts behind it. It is really good that the model has been validated using literature data and that some progress has been made toward non-conventional catalysts.
- At this stage of the project, it looks like the direction is good with an overlap of key characteristics with the data and model. Further iterations with greater accuracy are expected, as they will enable better discrimination between models.
- The accomplishments associated with the model development have been satisfactory. Incorporation into the overall FC-PAD model is a good result. Progress with University of Arkansas at Little Rock (UALR) catalysts, however, is limited. The cathode results are poor, and it is unclear how they may be improved.
- It is difficult at this point to judge how useful the model is. Its conclusion that smaller agglomerations are necessary does not seem viable on the surface, as so much work has been done on varying ionomer ink structures with very little benefit. It is unclear how the project team's model fits with the work done by Dr. Y. S. Kim at Los Alamos National Laboratory (LANL). The Pt directly on the microporous layer has a long way to go, and it is doubtful that it will amount to much. That particular structure is too poorly defined to be much of an aid in modeling. Also, even though performance is awful, it is unclear if the project team's model can predict that it would be so.
- There were only two accomplishments this year: development of the model and testing of UALR's Pt thin film electrode. The project is not on track. It is unclear how the project will meet its milestone.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- This project contains good collaboration with industry, universities, and national laboratories through FC-PAD.
- The organization and feedback structure of this project are excellent.
- This project is a well-coordinated effort between the team members.
- It seems like good teamwork is going on within this limited consortium.
- Collaborations with Ion Power and UALR are working well. Collaboration with FC-PAD partners at LANL, Lawrence Berkeley National Laboratory (LBNL), and Oak Ridge National Laboratory is evident. Additional collaborations for characterization of the electrode structure may be beneficial (e.g., Argonne National Laboratory with X-ray nano-computed tomography [nano-CT] efforts for characterizing pore structure, carbon, catalyst, and ionomer thickness).
- It is doubtful that the structures being generated by UALR will lead to either a compelling catalyst or an aid in modeling. At best, the team will have something like 3M's old nanostructured thin film catalyst, and they have reams of data to model that system. It is unclear what the difference is between the UTRC and LBNL models; if it is just dimensionality, it is not clear why LBNL is not doing all of the modeling.
- The role of each partner is clear, but it is unclear whether Ion Power has the expertise in electrode development to deliver the required structure that the project itself set up. Collaboration with FC-PAD is limited.

Question 4: Relevance/potential impact

This project was rated **3.2** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is relevant to the Fuel Cell Technologies Office, as it addresses the cost barrier for fuel cells. The project directly supports the current focus to improve high-power performance of fuel cells to decrease cost. The potential impact is significant. Addressing the transport limitations could lead to large improvements in power density, resulting in large cost savings.
- The seemingly simple approach in the model appears powerful in explaining results. This insight could easily be adapted for the toolbox of other projects.
- The HCD performance leads to large cost savings.
- A better understanding of transport at low loadings is needed, and the team's model may help this effort. The project team's use of past and published data is good, and it would be nice to see the team continue this effort with GM's current data, as well as Dr. Pintauro's interesting structures, and 3M's work with single-layer planar MEAs and mixed-layer MEAs, or the National Renewable Energy Laboratory's extended surfaces. The model would be useful if it would be resilient over numerous structures, and there are plenty like this out there already.
- Addressing HCD performance limitations is key to decreasing stack cost. There still remain questions as to the true source of these limitations at low-platinum-group-metal (low-PGM) loadings over the many length scales present in the MEA. Optimization and refinement of a catalyst-layer transport model and incorporation into the FC-PAD model will provide important insight.
- HCD performance is limited by mass-transport losses for low-PGM electrodes, so understanding the mass-transport losses using microstructures is important. This will help achieve the DOE's research and development goals. However, model validation for various catalysts needs to be done to make it more meaningful. One or two carbon supports with a Pt-only catalyst may limit the model's potential.
- The model needs to be improved to make an impact on technology development for fabrication of catalyst layers with low Pt loading.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The proposed future work of looking at variations in ionomer EW is logical, and the model predicts improvements after decreasing EW. The plans to modify the model for the thin film catalysts are appropriate. The plans to try to vary agglomerate size are not well defined, and it is not clear what variations will be achievable.
- The proposed future work is focused on MEAs/cathode catalyst layers (CCLs) with conventional catalysts, but model validation and demonstration using one of the SOA catalysts developed under other DOE-funded projects would be useful.
- While the proposed future work is relevant and obvious, how the project team will get there is not as clear. The explicit impact of the model is not defined, at least in the presentation. Specifically, it is not clear what changes are to be made to the CCLs to attain improved performance. Future work includes model development for the thin film catalysts but does not explicitly state how the team proposes to improve the MEA performance of the thin film catalysts. If this cannot be improved, then development of the model is not necessary.
- It is hard to understand whether the ultimate goal is a better model or an optimized MEA from using the model, or if the optimization will prove the model. Some of the team's optimization regarding ionomer–carbon ratios (I/C ratios) and EW is very easy to change and should be done. It is unclear what benefits the additional catalyst structures will provide and whether the model suggests that this will help. It is uncertain if this will help to validate the model; if so, and it is over a structure that has no relevance, perhaps this is not needed. There are plenty of additional interesting structures already developed in the public domain that the team can use to validate the model.
- There is no distinct separation between the MEAs made for optimizing the model and the MEAs that will achieve the target, while it is inherently implied that understanding from a (finished) model is key to achieving this target. It appears that the iterative cycle will be continued until project funding and time run out. The criteria and objectives could be more defined as steps in this process.
- The project plans are built on past progress and are too broad, not providing any specifics of the proposed work. No path is proposed in the future plans regarding the improvement of thin film catalyst layer performance.
- It is unclear how the project intends to meet targets.

Project strengths:

- The project provides a unique point of view; the model appears to be able to predict performance using bulk properties (which are readily measured) and does not need to vary properties with thickness of the ionomer.
- The project contains strong collaboration among team members, and the principal investigator and the team are experts in the field. The microstructure model development at three different length scales is another strength.
- The team has strong modeling capabilities, and the proposed novel modeling approach allows one to examine mass-transport limitations from a different perspective.
- This is a very strong team with a wide breadth of experience and capabilities. There is good collaboration to generate MEAs and collect data to put into models, which seems like an effective loop.
- A clear approach has already delivered a positive correlation, and the project partners seem aware and capable of addressing all anticipated issues to make the MEA and model more sophisticated.
- The strength of the project lies in the incorporation of spherical diffusion into the general CCL transport model.

Project weaknesses:

- To this point, the model has not been tested over many different ionomers, catalysts, and catalyst contents, though some of that is planned. It seems much more could be done by fitting to data by others, including what must be a huge archive of UTRC and LBNL data. For example, dozens of I/C ratio studies have been

done, which usually show a rather subtle effect over a given range. The team seems to predict that it could lead to a large improvement.
- The combination of conventional catalysts and thin film catalysts as two model research objects may also lead to two distinct models that describe the data well but lack correspondence between limiting factors in both catalyst layers. This is to be determined.
- It is not clear how much of a variation the team will be able to produce in terms of agglomerate size and other parameters of interest in the experimental project.
- There is no clear link between model development and specific changes to traditional CCLs. The thin film catalyst is not performing well.
- The thin-catalyst-layer approach does not seem like a viable path to mitigating mass-transport limitations at HCDs.
- There is a lack of model validation using SOA catalysts and MEAs.

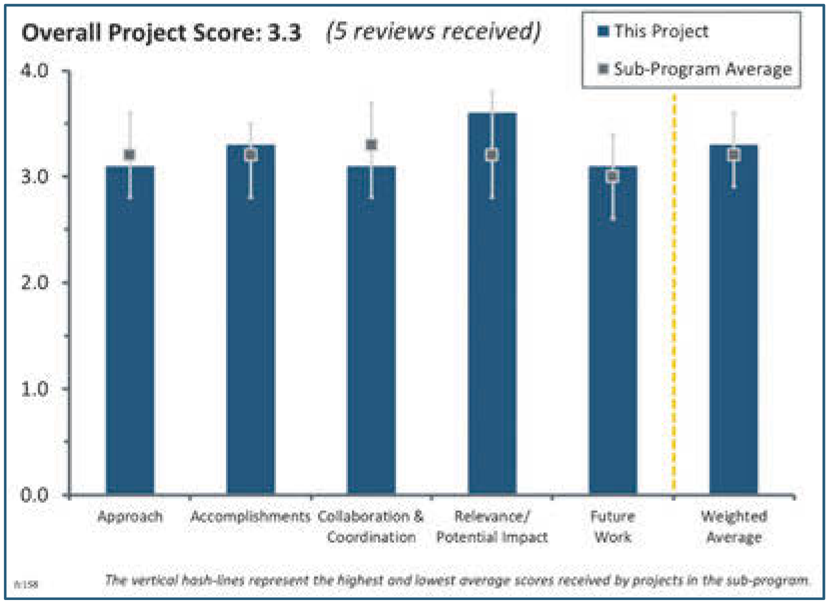
Recommendations for additions/deletions to project scope:

- Additional collaboration on the electrode characterization could be beneficial (using X-ray nano-CT, for example).
- It is recommended that the project use data from other groups with very different structures to test the model. Dropping the catalyst development work is also recommended.
- It is suggested that the project incorporate a new go/no-go point associated with the thin film catalysts to demonstrate acceptable cathode performance before any further development or model development.
- The electrochemical characterization and, in particular, the measurement of the limiting factor could be enhanced by the application of an impedance spectroscopy. This is to demonstrate resistance fingerprints in varying conditions, for example, in 100%, 20%, and 10% oxygen that has been diluted in nitrogen or helium (something like a half-helix). This step could further complement the model and show what key (experimental) measurable characteristics are indicative of the specific modeled issues in diffusion limitation.
- Regarding non-conventional catalysts and catalyst layer structures, the focus should be on the catalyst that has potential to get commercialized. Many efforts have been put into thin film Pt catalysts without much interest from industry. SOA catalysts, nanofiber electrode structures, or other new catalyst layer structures should be considered for validation.
- The deposition of thin Pt layers by sputtering should be deleted from the project scope. Electrodeposition is a more viable approach, as it provides much more flexibility compared to physical methods, in terms of microstructure control. This approach has been successfully demonstrated by Dr. Adzic’s group within the DOE-funded Hydrogen and Fuel Cells Program.

Project #FC-158: Fuel Cell Membrane Electrode Assemblies with Ultralow-Platinum Nanofiber Electrodes

Peter Pintauro; Vanderbilt University

Brief Summary of Project:



Particle/polymer nanofiber mat electrodes are a promising alternative to conventional fuel cell electrode structures. This project seeks to better understand and further improve the performance and durability of low-platinum-loaded nanofiber mat fuel cell electrodes and membrane electrode assemblies (MEAs). Mat electrode MEAs with highly active oxygen reduction reaction (ORR) catalysts for hydrogen–air fuel cells will be fabricated, characterized, and evaluated. The project will focus on nanofiber cathodes with commercial platinum–alloy catalysts and platinum–nickel octahedral catalysts containing various ionomer and blended polymer binders.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The objectives of this Vanderbilt-led project are clearly defined, as are the barriers it aims to address. While not unique (electrospinning has become quite popular in energy research worldwide), the approach is viable and promising, especially following the recent introduction of a water-soluble binder.
- The approach is to tune the structure of the catalyst layer by shaping the conventional Pt/C and ionomer into nanofibers. The fiber approach to catalyst layer construction yields surprisingly excellent results. The partnership with the Georgia Institute of Technology (Georgia Tech) with new catalyst material appears to be a distraction from the overall project approach.
- The project attempts to improve high-current-density performance and durability using an alternative approach of coating the electrode with sub-micron-size fibers; the advantage of this approach is fundamentally unclear, as the structure is not maintained after MEA fabrication.
- The electrospun electrodes are showing early promising results. The unanswered question deals with why, and inherently why these electrodes would be expected to be an improvement over more conventionally supported catalysts that use the same Pt–alloy catalysts. Early characterization results are giving some clues, but more effort is needed here (and, to the team's credit, is listed in future work). The Fuel Cell Consortium for Performance and Durability (FC-PAD) is well suited to this task. A more systematic approach is necessary to understand the interaction between structure, materials, and conditions on performance (i.e., questioning how ionomer-to-carbon-weight ratios (I/C), porosity, ionomer, carrier choice, etc. affect polarization curves, stability/durability, loss contributions, etc.).
- The idea to use electrospun fibers in fuel cell catalyst layers is excellent. However, the materials could be characterized much better. Beyond a scanning transmission electron microscopy (STEM) micrograph, there was little information. The authors should characterize the pore size distribution with mercury and/or N_2 porosimetry. The performance of the fuel cell will be highly dependent on the pores available (water management), so their characterization in the catalyst layer, preferably with ionomer, is critical. The type of

gas diffusion media used will also play a critical role in water management, as well as compression. While the team might be making these considerations, none of this information is in the presentation. As presented, the results were highly empirical.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The excellent fuel cell performance of the nanostructure fibers speaks for itself. The project contains excellent results.
- The performance of the electrospun nanofiber MEAs, especially those from Gen 2, is impressive, either already reaching or closely approaching the set of go/no-go performance targets for December 2018. The high porosity of the fibers appears to benefit the mass transport of oxygen (with more than tenfold improvement versus the sprayed-electrode baseline), facilitating water management and ultimately helping MEA performance at high current densities. The replacement of polyacrylic acid with an easily removable blend of an ionomer and carrier has resulted in a noticeable gain in the performance of Gen 2 MEAs relative to Gen 1. This, in particular, makes the latest-generation electrodes perform better than Gen 1 at low relative humidity (RH). The observed variation in the activation losses with the three electrodes is puzzling. It is relatively significant, possibly obscuring the true values of other performance losses, especially those associated with the mass transport (slide 10). There has been little progress in the development of PtNi/C octahedra catalyst at Georgia Tech. Catalyst development is the weakest part of this otherwise very good project.
- There is very nice progress (>900 mW/cm^2, <40% loss after 30K load cycles) at this relatively early stage. This does appear to be at a relatively high cathode stoichiometry, so it would be good to see the performance under a more applicable stoich (1.5–2.0) at high current densities. The baseline (sprayed) performance is also sub-par. The performance should be compared to a better-optimized Pt-Co MEA from, for example, other DOE projects (both in and out of FC-PAD). It is recognized that the nanofiber MEA is likely not yet optimized, so improvements on this are expected as well. While the polarization loss plot (on slide 10) shows improvement over the baseline sprayed catalyst, it does oddly show higher mass transfer losses (lower RH plot). Perhaps this is a measurement artifact, but it should be investigated. The principal investigator (PI) noted a loss in performance (max power density) going from 0.2 to 0.1 mg/cm^2 *total* loading (906 W/cm^2 versus 809 W/cm^2). However, the cathode remained relatively constant (0.1 mg/cm^2 versus 0.09 mg/cm^2, perhaps within uncertainty of measurement). It is questionable whether that difference would be due to reduction from a thick (0.1 mg/cm^2) anode to a very thin (0.019 mg/cm^2) anode. The difference may have been due to either a poor anode or, more likely, sample variation. Thus it is recommended that the project continue with a relatively fixed anode loading (at either 0.05 mg/cm^2 or 0.025 mg/cm^2) and focus on the cathode, with multiple samples tested to comprehend variation.
- Progress is made toward DOE goals; however, this is done (as presented) via an empirical approach. There is more of a focus on materials discovery/patenting rather than understanding why the materials are performing well. The researchers could do a better job presenting the state-of-the-art by using a Gore standard, or data published by General Motors, for comparison. The sprayed standard has very poor performance versus the state of the art, making the Vanderbilt results look more favorable compared to DOE results. It is not clear why the PtNi electrocatalysts should perform better than the commercial PtCo.
- There is good improvement over the previous generation's process. However, because the performance of the baseline spray process is awfully poor, benchmarking the progress is impossible. Overall, the data quality is poor.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The collaboration with Nissan is excellent, and the collaboration with FC-PAD is also good.
- The team appears to be working well together, and all researchers contributed to the project.

- The integration with FC-PAD to characterize the MEA is appreciated. It is recommended that this, combined with a systematic variation of the MEA processing (I/C, ionomer, carrier, electrospinning process parameters, etc.), be the focus for the following year. Nissan should be capable of building and performance-testing the final MEAs. The performance of the baseline PtCo-sprayed catalyst is surprising; this suggests some extra effort is also warranted on ensuring that the final MEAs are optimized. The integration of Georgia Tech's shaped catalyst with the project's main focus (electrospun nanofibers) is not clear.
- The efforts at Vanderbilt and Nissan Technical Center North America seem to be well integrated and complementary, with the two teams collaborating effectively. The contribution of Georgia Tech is less evident, clearly because of problems with obtaining a competitive PtNi catalyst. Collaboration with FC-PAD laboratories (Oak Ridge National Laboratory, Lawrence Berkeley National Laboratory, Argonne National Laboratory, and Los Alamos National Laboratory) has been generally very good, helping with the characterization and performance verification of nanofiber electrodes.
- As the project is an FC-PAD member, it would be nice to see more leveraging of the national laboratories' capabilities, especially in the MEA evaluation, as the data quality is quite poor.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Durable, high power densities at low/ultralow-platinum-group-metal (PGM) loadings are the key enabler to automotive fuel cell commercialization. Both materials (i.e., catalyst and support) and an understanding of their interactions (FC-PAD) are fundamental to achieving this goal. This is the type of work we need.
- This project is very relevant to the DOE Hydrogen and Fuel Cells Program goals and objectives. It promises to be successful, and if so, its impact on MEA technology could be substantial.
- The project has the potential for a major impact on improving the commercial viability of fuel cell systems for automotive applications (i.e., the overall DOE objective).
- High-current-density performance and durability are very important.
- The team is working toward DOE goals but in an empirical fashion. It would be useful to have some insight into why the materials are performing well and what parameters effect improvements.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work ensures continuity of the research performed so far, with a focus on what it promises will be an incremental improvement in performance through process optimization and assessment of electrode durability using standard accelerated stress tests. The PI lists several questions to be answered in the remaining part of the project. These are all important questions that, if successfully addressed, could help advance the electrospinning technology for fuel cell MEAs.
- The planned future work is good, but a more cohesive approach providing answers to science questions would be better. Less focus on proving the DOE laboratory theory of oxygen resistance as a limiting factor in performance would be helpful. The team should focus more on gas diffusion media/water management. The use of alternative catalysts should be considered—without waiting for the Georgia Tech materials. The team should focus on using different ionomers; this is being discussed but not done. Also, the characterization of the pore size distribution in the catalyst layer is likely critical to better performance.
- The future work proposed on slide 19 is what is needed. Specific details, however, will require fleshing out. It is unclear what material and process parameters are going to be varied and which ones will be subject to the battery of tests and characterization available to the team. Some systematic characterization of the process variables is needed (I/C, etc.). Perhaps a design-of-experiments approach can be employed. Startup/warmup needs to be addressed. It would be good to know how the material performs at -30°C, 0°C, and 30°C; it is recommended that the project run the U.S. DRIVE Partnership Fuel Cell Technical Team robustness protocol.

- The proposed work should focus on scale-up, durability, and cost analysis of fiber fabrication. Some justification should be made for the manufacturing costs of the electrodes, since it most definitely will be higher than simply ink casting conventional Pt/C.
- It would be nice to see more progress in integrating high-activity catalysts.

Project strengths:

- This is a well-designed project targeting enhancements in the MEA performance via the electrospinning of porous nanofibrous catalysts and ionomers. This progress has been excellent in the past 12 months, with project targets likely to be reached, and possibly exceeded, by the project end, if not earlier.
- The electrospun fibers are very interesting and hold much promise. This might also be interesting for liquid fuel cells that require higher porosity in the catalyst layer. The team is good and holds potential for more in-depth studies.
- The team has developed an electrode/MEA exhibiting early promising performance. The FC-PAD team brings a wealth of analytic and diagnostic capability, which is well suited to the project approach.
- The project could have an obviously big impact in power density and Pt utilization targets.

Project weaknesses:

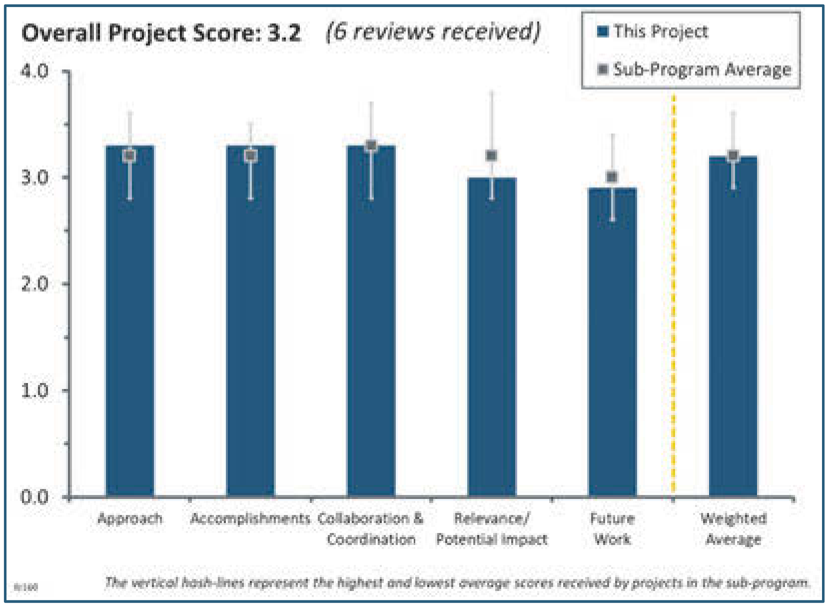
- No weaknesses come to mind.
- There are not too many weaknesses in this project, except for the questionable value of the PtNi controlled-shape catalyst research at Georgia Tech.
- There is no clear weakness, although it is unclear how the Georgia Tech shaped catalysts integrate with the bulk of the project.
- The materials are poorly characterized. The electrochemistry at Nissan is focusing on answering issues of ionic and oxygen transport, with little emphasis on water management. There is no discussion of ionomers, gas diffusion media, or the role of MEA compression on cell performance. The project could likely hit DOE goals easily if the team would focus on the water management areas (i.e., gas diffusion and compression). The researchers should provide more technical insight into the pore size distribution in their electrospun fibers.

Recommendations for additions/deletions to project scope:

- The viability of PtNi shape-controlled catalysts from Georgia Tech should be verified, and if there is doubt, the resources should be reallocated elsewhere within the project. A considerable part of this research should focus on the impact of electrospinning on electrode durability and understanding the origins of the benefits rendered by the electrospinning of electrodes. The latter task will require correlating fuel cell performance and the comprehensive characterization of the electrodes and MEAs (likely to be provided by the FC-PAD laboratories).
- A de-focus on the Georgia Tech shaped catalysts is recommended. It is suggested the team increase focus on systematic parameterization (perhaps using a design of experiment) and optimization of the process variables (such as I/C, percentage of PGM, electrode thickness, ionomer, carrier, electrospinning process variables, etc.), complete with characterization and testing. It is also recommended the team include multiple samples where needed.
- The elimination of catalyst work at Georgia Tech is recommended—fibers need to be better characterized before the role of alternative catalysts can be understood.
- A cost analysis of manufacturing electrodes is necessary. Durability and drive-cycle operational stability should still be addressed.

Project #FC-160: ElectroCat (Electrocatalysis Consortium)

Deborah Myers (Argonne National Laboratory) and Piotr Zelenay (Los Alamos National Laboratory); Los Alamos National Laboratory



Brief Summary of Project:

ElectroCat (the (Electrocatalysis Consortium) was created as part of the Energy Materials Network in February 2016. The goal of the consortium is to accelerate the deployment of fuel cell systems by eliminating the use of platinum-group-metal (PGM) catalysts. ElectroCat and its member laboratories—Argonne National Laboratory, Los Alamos National Laboratory, National Renewable Energy Laboratory, and Oak Ridge National Laboratory—will develop and implement PGM-free catalysts and electrodes by streamlining access to unique synthesis and characterization tools across national laboratories, developing missing strategic capabilities, and curating a public database of information.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The team has developed an excellent approach to the work, proceeding to answer key questions in the development of PGM-free catalysts in a very structured and systematic way: by measuring key parameters in the catalyst, developing measurement techniques, and establishing process–composition–activity relationships. The high-throughput synthesis, characterization, and performance evaluation work has provided an effective way to develop relationships between catalyst composition and processing variables, with resulting catalyst properties. X-ray computed tomography (CT) work appears effective at increasing the understanding of the catalyst layer structure. The automated dispensing of inks and the fabricated electrode with a catalyst/ionomer gradient over the length is an effective way to provide repeatable fabrication and to understand ionomer composition effects. Modeling work is necessary and provides useful insight into active sites and linkages with electrode design. The approaches to begin the molecular probe of durability are good.
- The project approach is excellent, encompassing the full array of materials development, state-of-the-art characterization, and modeling capabilities that are available within ElectroCat. These capabilities are appropriately applied toward developing understanding and resolving the key challenges of non-PGM oxygen reduction reaction catalysts.
- This project has a very good combination of materials discovery and tool development. It would be good if the project explained the difference between ElectroCat (a consortium of national laboratories) work and funded project work.
- This project partners with very strong leaders from four national laboratories, each with proven capabilities and expertise in the key technologies that are critically important for project success.
- This consortium is advancing state-of-the-art catalysts for PGM-free fuel cells, developing new tools, and improving understanding of the catalysts. A minor shortcoming is the narrow focus on mainly an Fe-N-C

catalyst that may possibly be inherently unstable, but at this point, no other PGM-free catalyst is competitive.

- Extensive ex situ and in situ characterization of PGM-free catalysts was done. However, the focus is primarily on Fe-N-C, and therefore, the ultimate usefulness of this work will be limited. The high-throughput addresses only a narrow range of parameters that are expected to give only incremental improvements. Stability is not a criterion in high-throughput screening; it is hard to see any innovative approach that will significantly improve the volumetric activity and stability.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team has made good progress and has exceeded a key milestone. Excellent progress has been achieved in a number of areas: the correlation between composition and activity, the development of molecular probes, the characterization of important processes and composition variables, and the development of a repeatable fabrication process and further developed models.
- The project has made excellent progress across multiple fronts, including furthering understanding of the active sites and, more importantly, degradation of the active sites and resultant performance loss. The team is making excellent use of several advanced characterization methods toward this effort.
- A method for estimating the demonstrated active site density will help with understanding and improving the active site structure. NO_2- was successfully used as a molecular probe, but the catalyst will also have a nitrogen species, so it is uncertain if this is a Fe-N species interaction with a probe molecule.
- The active site probe work is a major accomplishment in this field. The durability characterization work was very enlightening.
- This project team has shown significant and continuous progress in each of the four key areas of development: catalyst development, electrode and membrane electrode assembly (MEA) development, high-throughput fabrication, and modeling. The lead investigators have placed each of these areas under the leadership of proven organizations that are consistently meeting their interim targets. Progress is approaching the project goals. One area that requires additional focused attention is the migration of Fe. While this report shows Fe migration through the catalyst layer away from the membrane, the test time is extremely short, and many operating modes still need to be tested. To the extent that Fe reaches the membrane in any of the operating modes, the resulting Fenton reaction will severely limit the membrane durability. Since this project introduces Fe into the catalyst, it must define a solution path.
- The molecular probe to determine the active site/site density is interesting. There should be a paper study to estimate what is needed for this catalyst family to be practically useful. The primary focus is on initial performance. It would be interesting to benchmark the materials against a state-of-the-art PGM catalyst on performance and durability to understand the status, and justify if there is any tangible progress. Each year, progress should be benchmarked against a state-of-the-art PGM catalyst at relevant operating conditions (air, Q/dT).

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The collaboration across all ElectroCat members is clear and directly relevant toward achieving desired project outcomes.
- There is excellent coordination between partnering laboratories for material and tool development.
- Work appears to be well coordinated, cohesive, and comprehensive.
- This project has plenty of collaboration. A minor concern is the lack of original equipment manufacturer collaboration.
- This project contains very close collaboration between national laboratories. The lack of partnership with any major industrial players begs many questions. The relevance and impact of the project are likely small.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Fuel cell stack cost is still one of the main challenges in DOE's Fuel Cell R&D sub-program. Eliminating PGM completely will definitely help meet the material cost target, but performance and durability targets for transportation application will be challenging to meet. A combination of very low-PGM (i.e., 1% or 2%) and highly active PGM-free catalysts may be able to meet the cost and performance targets. If DOE agrees, this should be explored as one of the options at the end of the project. The main focus should be on PGM-free catalyst development.
- The PGM catalyst is projected to be the most expensive single contribution to the cost of the fuel cell stack. Eliminating the PGM while maintaining the current level of specific power, power density, peak energy efficiency, and durability will significantly accelerate the deployment of fuel cell systems.
- The project is relevant to long-term goals for lowering fuel cell cost. An immediate commercial impact is not likely.
- The project is well aligned to address the key cost, performance, and durability barriers that are slowing commercialization of fuel cell technology. One area of concern is that the relatively large effort within the Fuel Cell Technologies Office for PGM-free catalyst development may not ultimately result in commercial fuel cells, and if it does, the timeframe may be measured in decades. The PGM-free field has made excellent progress in improving the activity and performance over the past decade (further gains are still needed), but the significant durability and performance degradation issues that are evident over periods of tens of hours (vs. 5000- to 8000-hour targets for fuel cell electric vehicles) under rather benign conditions are extraordinarily concerning. Real systems will spend considerable periods of time at relatively high potentials (e.g., >0.7 V) and have start–stop events, the latter of which is the elephant in the room (i.e., carbon corrosion stability). The project is performing the right type of work to understand the durability, but a key question is whether this class of catalysts will ever be sufficiently durable for commercial applications—this should be assessed as soon as possible. Recently, PGM-based catalysts, supports, and electrodes have rapidly been achieving DOE performance targets, and an additional loading reduction factor of 2 may substantially address most of the remaining gap for achieving the ultimate target of $30/kW. The questions/concerns around PGM-free catalysts are not reflective of the high quality and excellent research being conducted in the project, but should be addressed to understand the relative priority of this class of materials with relatively longer timeframes for potential commercialization.
- The work from this project is highly valuable and of high relevance for the development of PGM-free catalysts. While much progress has been made, the path of these catalysts to high-power density and long durability is still uncertain, which may limit applicability.
- Reducing the amount of PGM is important, but the impact of a PGM-free catalyst on cost is overstated. The use of iron and the low stability of the catalyst must be addressed.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The future work is appropriate. It is recommended that the project increase work on understanding the electrode design and increase efforts on understanding the degradation mechanism.
- This consortium is making good progress, and no major changes are needed. Some expansion of the types of catalysts that are being analyzed would be beneficial.
- Overall, the proposed future work is good, continuing fundamental studies across the breadth of topics necessary to advance the PGM-free activity class. Additional near-term work should assess carbon corrosion stability, one of the primary (and perhaps fundamental) barriers with carbon-based non-PGM catalysts.
- Short-term durability testing has identified some potential issues. Longer-term testing, as well as a broader test base, is necessary. The potential risk with Fe is high, and so a solution path is needed. The larger MEA area has to be demonstrated.

- The project's proposed future work consists of continuing development on Fe-based catalysts, which attract little interest from industry. There is a large amount of work in the study of performance and stability of a catalyst family that might not be relevant.
- More efforts on MEA optimization would be needed.

Project strengths:

- The project's strengths lie in a comprehensive and cohesive effort to systematically study catalyst composition and processing parameters' correlations with catalyst activity. Strong characterization tools are incorporated, and the modeling approach is informing the work. This is an excellent team.
- The project team consists of leading experts in the PGM-free catalyst field and includes expertise in PGM-free catalyst design, synthesis, and characterization. The project has access to the necessary state-of-the-art characterization methodologies needed to make rapid progress.
- This project is advancing catalyst performance, test/analysis capabilities, and fundamental understanding in the field of PGM-free catalysts.
- This project group is very experienced, as shown by the members' previous work. The lead investigators and their partners are capable of successfully completing this program.
- This is a team of expert researchers and tool developers.

Project weaknesses:

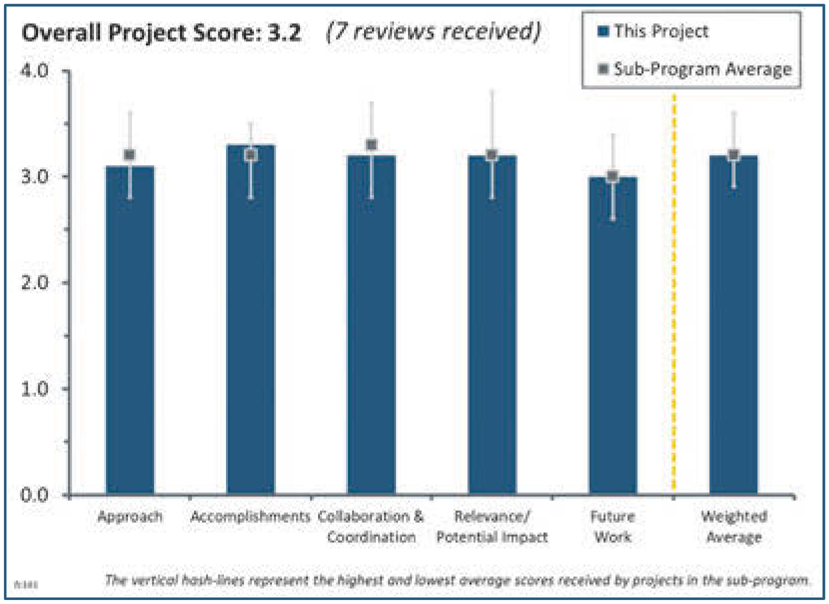
- No real weakness was identified.
- The primary project weakness is that the durability of PGM-free catalysts may not be addressable, which would significantly limit the utility of this technology commercially within the next decade(s). Carbon corrosion stability may be a likely key fundamental barrier, which should be assessed in the nearer term.
- Current Pt anode loading in an MEA is still higher than in a PGM MEA. Lower anode loadings should be explored. It is safe to assume there is no effect of anode loadings, but, to avoid any surprises, anode loadings should be lowered at an early stage of the project.
- A materials and capability development investment of $4M/year is quite large, considering the relevant output from the project. There is a negligible interest from major industry players.
- This project needs to develop a solution path to verify that Fe will not leach out of the catalyst layer over time, at all operating conditions that can be anticipated.
- The project is focusing on Fe-N-C catalysts that seem to have inherent durability limitations.

Recommendations for additions/deletions to project scope:

- It is recommended that the project increase efforts on modeling the electrode structure and aligning a "possible" future catalyst design with an optimized model design. For example, it is suggested that the project take into account the realistic concentration of achievable active sites, electrode thickness, and transport effects. Efforts should be increased to understand the degradation mechanisms.
- Some expansion on the types of catalysts that are being analyzed would be beneficial (i.e., other metals, non-metal, polymeric, other carbon dopants, etc.).
- A combination of low PGM (1%–2%) and the best of PGM-free catalysts should be explored as an option in case PGM-free catalysts do not meet performance targets.
- The project should dramatically increase focus on addressing durability. Activity and performance at beginning of life is approaching Pt electrodes (within a factor of 2), but durability is the key barrier.

Project #FC-161: Advanced Electrocatalysts through Crystallographic Enhancement

Jacob Spendelow; Los Alamos National Laboratory



Brief Summary of Project:

Los Alamos National Laboratory (LANL) seeks to design active and durable oxygen reduction reaction (ORR) catalysts based on fully ordered intermetallic alloys on highly graphitized nitrogen-doped carbon supports and demonstrate them in high-performance membrane electrode assemblies (MEAs). Synthetic work is guided by computational ORR kinetic studies, and each round of synthetic development is further guided by feedback from MEA testing and characterization studies.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- Atomic-level ordering is a very good approach for durable catalysts; the project has several catalyst candidates that were developed simultaneously.
- The approach of this project is in agreement with other similar projects that are aimed to address the U.S. Department of Energy technical targets for Pt-based systems.
- The multiple approaches for risk mitigation and technique comparison are good. This is a good team that is clearly working together. The support work seems less valuable than catalytic development. There is concern that the support work will divert effort away from the strong catalytic developments.
- This project utilizes a wide pool of characterization techniques, as well as computational tools, to guide the design and synthesis. Different synthesis techniques and processing methods have been employed to achieve atomic-level ordering to increase performance and durability of Pt-based catalysts.
- The proposed approach is addressing the project goals. The only minor concern is with the project design, as it is not clear how the efforts of the catalyst synthesis collaborators are related, or beneficial, to one another.
- The approach is based on the hypothesis that the intermetallic alloy structure will enhance activity and stability. The idea has been tried many times without sufficient execution. Therefore, the risk is somewhat high. The project employs several approaches to prepare the structure, and hopefully some approach(es) work. The team evaluates MEAs for performance.
- While some catalysts in this project have shown promising mass activity, they all show quite low electrochemical surface area (ECSA). The participants need to clearly demonstrate that they have a path to achieve performance targets at >1.5 A/cm^2. This could be by increasing ECSA, increasing mass activity, or reducing local oxygen transport losses. Regardless of the approach, there is currently no clear evidence that this will be achieved.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Thus far, there has been excellent progress from a fundamental aspect in regard to characterization and evaluation.
- The team has met some difficult targets this year. The team showed some characterization results supporting the importance of the ordered structure. The presentation of the data is clear and fair.
- The project is on track and is focused on achieving DOE goals for cathode catalysts.
- The project is clearly laid out; clear and significant progress has been achieved.
- Progress has been made in the synthesis and characterization of intermetallic Pt alloys with transition metals. However, the idea and execution cannot be entirely associated with this project, considering that identical systems have been proposed and reported before. Nanoparticles presented cannot be referred to as high-quality materials. The main focus in this project is to induce control of the structure; nevertheless, transmission electron microscopy (TEM) micrographs, X-ray diffraction patterns, and cyclic voltammetry (CV) do not indicate a high level of ordering. Instead, that is likely to be random effect. Moreover, particle size distribution is significant, including size and irregular shape. On the other hand, the measured performance of the MEA did exceed the DOE technical targets.
- The team shows promising results for certain metrics or catalysts, yet scale-up needs to be demonstrated. Results on structural changes upon accelerated stress tests (AST) are interesting and useful for understanding the key phenomena. Advanced characterization studies nicely complement the data from MEA testing.
- While some of these catalysts show decent mass activities, their relatively low ECSA is a concern. Only the LANL face-centered-tetragonal (fct)-CoPt appears to have an ECSA approaching a value close to what will be required for automotive applications. If the principal investigators believe this problem can be overcome through reducing local transport losses, they should provide evidence/modeling to show what combination of ECSA, mass activity, and local transport losses will be required.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- There has been excellent collaboration among the team members, which is evident from results.
- This multi-method approach helps the industry as a whole by focusing on what methods are best for these catalysts.
- The team has good collaboration and coordination, especially on synthesis of catalyst structures and their characterization and testing.
- Collaborator roles are clearly delineated.
- All project partners appear to be engaged.
- While the project has collaborators, it seems there are three parallel projects being pursued.
- The team uses national laboratories' capabilities well. Results from sub-contractor universities are fewer. Participation from EWII Fuel Cells was not evident.
- It is unclear how the result of this work will be transferred to the market. There was no talk with a major industrial player. The precious metal market is very competitive, and it is unlikely that a new small player can profitably compete. It is debatable whether materials development at this level is appropriate at a national laboratory.

Question 4: Relevance/potential impact

This project was rated **3.2** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project's scope and goals align well with the DOE objectives on improving catalyst performance and durability for fuel cells.
- This project is addressing DOE targets and, if successful, will be impactful with regard to reducing fuel cell cost.
- This project is relevant to DOE's fuel cell research and development roadmap to meet DOE's 2020 target.
- Durable high-activity catalyst development is important.
- This is very relevant work. One limiting factor is perhaps the high amounts of transition metals that are currently being used. It is unclear whether there is a plan to reduce the amount of cobalt.
- The modeling work is of value. However, until clear evidence of or a plan for how high current density performance will be achieved is presented, it is unclear how impactful the work will be.
- The potential impact of this work cannot be seen as high, considering that other programs have proposed and made identical systems.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work plans are well described and are in line with the overall project goals.
- The project is on track, and the proposed future work is the logical next step. A minor potential issue is that the catalyst down-select process to identify "promising catalysts" was vague. No technical targets were given for what catalysts must achieve to be down-selected.
- Scale-up and integration work is certainly of importance. However, as mentioned, some modeling effort to demonstrate that the partners have a viable approach to achieving high current density performance is required (although the modeling effort does not have to be extensive).
- The high content of transition metals should be addressed. Additional modes of operation may cause significant decay and cobalt leaching.
- Future work is a logical continuation of this effort, which is supposed to address challenging steps such as scaling up and characterizing 50 cm^2 MEAs.
- Down-selection of a promising catalyst is mentioned in the future work, so it is expected that the team will do this earlier rather than later so efforts can be focused on the best catalyst.
- It is unclear what the down-selection criteria are and whether there is a go/no-go decision point for unproductive approaches/partners.

Project strengths:

- The team's approach with different synthesis methods guided and supported by various testing and characterization is a strength. The project partners, a decent set of publications, and presentations were also project strengths.
- Modeling appears to be providing useful guidance for catalyst synthesis. Several catalysts with promising mass activities have been prepared.
- A project strength is the strategy to work with well-controlled Pt alloy nanoparticles, well-executed electrochemical performance in MEAs, and careful TEM studies.
- National laboratory and university collaboration is strong. Exploring new ideas such as the hydrogel approach is also a strength.
- This is a good approach. The team has shown solid work, strong results, and good collaboration.
- LANL is developing alloy catalysts that so far show promising activity and stability.

Project weaknesses:

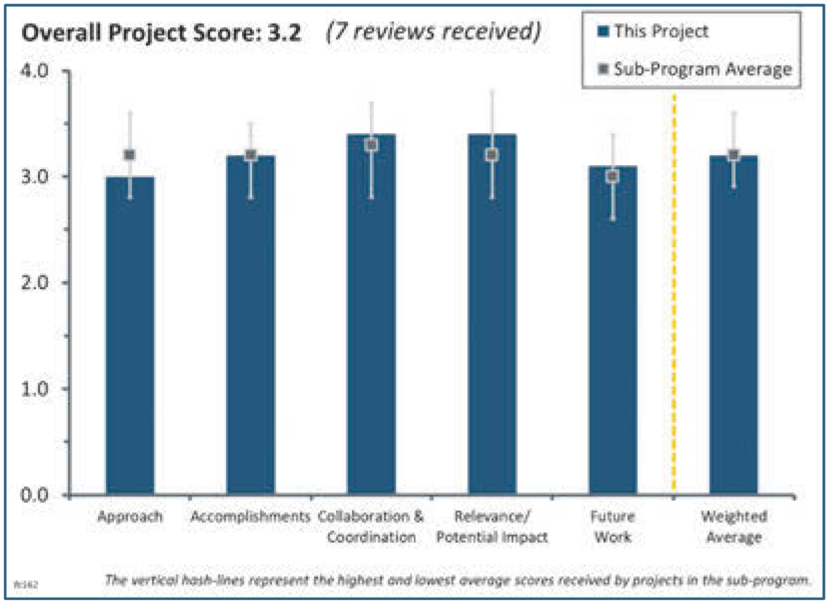
- The path to achieve high current density performance is rather ambiguous and seems to rely on anticipated advances in ionomer or other methods to reduce local oxygen transport.
- High activity has been achieved, but with high transition metal content. N-doped carbon supports distract from the core catalyst work.
- There are no specific project weaknesses, although scalability is an overall concern.
- Multiple synthesis routes are being pursued, but it is not clear how these routes are complementary.
- The outcomes would be identical to those other programs have already achieved.

Recommendations for additions/deletions to project scope:

- The team should eliminate carbon support development and perhaps attempt to deposit the catalyst on more existing types of supports for comparison.
- To fully utilize the team's potential, the lead researchers should focus on systems that are unique to this project.
- It is recommended that LANL down-select the two best catalysts and focus the electrode work. Otherwise, the experimental matrix may become too large.
- The team should immediately add a strong focus on how to achieve high current density performance.

Project #FC-162: Vapor Deposition Process for Engineering of Dispersed Polymer Electrolyte Membrane Fuel Cell Oxygen Reduction Reaction Pt/NbO_x/C Catalysts

Jim Waldecker; Ford Motor Company



Brief Summary of Project:

The objective of this project is to develop, integrate, and validate a new cathode catalyst material by developing and optimizing a vacuum powder coating physical vapor deposition (PVD) process. Project tasks include (1) development of a new cathode catalyst powder made of titanium, niobium oxide, and carbon; (2) improvement of the PVD process for the manufacture of the catalyst powder; (3) cost-effective scale-up of the PVD process; and (4) integration of the developed cathode catalyst powder into established fuel cell manufacturing processes.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project team, led by Dr. Waldecker, will address the main issues with fuel cells for the automobile industry to produce a high-performing membrane electrode assembly (MEA) at rated power (with the U.S. Department of Energy's recommended Pt loading), while the electrocatalyst allows an increase in durability to the targets described in the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP). The relevance, targets, and proposed work were clearly presented in the slides and were described during the review. The team, under the supervision of Ford Motor Company (Ford), will explore design, synthesis, evaluation, and scale-up of a Pt-NbO_x/C catalyst, which will be integrated into the catalyst layer of the electrode. The main challenge of these materials is the low reproducibility of almost all synthetic approaches (which the team has already experienced); however, the well-known synthetic expertise of Exothermics, Inc. (Exothermics) and Oak Ridge National Laboratory (ORNL), in combination with the leader of MEA fabrication, EWII Fuel Cells, will no doubt make the project feasible. It should be mentioned that the principal investigator (PI) spent enough time during the beginning of the presentation explaining to the audience all key aspects of the project, the role of team members, and challenges faced. The team leader also gave a full picture of the technology and explained the logic behind the selected tasks for budget periods I and II, as well as the milestones.
- The PVD approach to make catalysts using direct Pt deposition onto the support material is a good way to eliminate the complexity of a wet catalyst synthesis process. 3M practices a similar vacuum-assisted sputtering process to deposit Pt on carbon whiskers to make 3M's nanostructured thin film catalyst. The approach is viable and has all the advantages cited by the PI in this presentation on slides 5–7. The simplicity of the PVD process is expected to make it cost-effective. However, the team may need to fine-tune their cost estimate as shown on slide 7. The processing cost estimate by Exothermics may be early, and going forward, the team needs to validate the estimate. Since the team is not going to anneal PVD-made catalysts, their stability under ink-making conditions (such as ultrasonication, homogenizer, etc.) needs to be evaluated by the team.

- The overall approach of using niobia to try to stabilize Pt offers some potential advantages. The approach of preparing catalyst powder samples using PVD is unique and has potential for a lower-cost catalyst-preparation method. The work has been focused on meeting the activity milestone and not on demonstrating a key hypothesis and differentiating factor for this project (i.e., the hypothesis that niobia improves Pt durability). The work should have more focus on addressing whether niobia improves durability. The approach to date has lacked focus on characterization and on understanding what is happening in the system. Characterization of the samples has been lacking. The project to date does not appear to have effort directed toward determining how much of the carbon is covered by niobia, or the niobia particle size. These are expected to be key parameters, considering the hypothesis put forth that the niobia helps pin the Pt particles. If the goal is for niobia to improve Pt durability, it is not clear how the very low (some less than 0.2%) niobia loading will contribute.
- The approach is clear and proceeds logically. The approach thus far has not focused on durability, which will be critical in establishing the benefit of Nb, but this is to be addressed in the coming period. Of particular interest is whether the relatively low Nb composition examined would be enough to improve durability, or whether the performance would suffer if a higher Nb composition were needed.
- The PVD method indeed has great potential, but the specific advantages over other methods have not been highlighted sufficiently (for example, the control over oxygen stoichiometry NbO_x).
- The project team is working on simplifying a PVD process for improved reproducibility. However, to date, the PVD process appears to have issues with "line of sight," and getting uniform niobia does not appear to have happened. There are issues with reproducibility between the two systems in use; either this needs to be fixed, or one of the systems needs to be discontinued. At least from the discussion, it seems the tumbling of the carbon is not yet as reproducible as it needs to be. The team has shown various loadings of niobia on carbons; however, the weight percent of NbO_x has been relatively low—samples range from 0.5% to 13.3% (on slide 12), and slide 5 shows a 17.6 wt.% NbO_x sample. However, it seems unreasonable that a full coverage on the acetylene black can be obtained at any of these weight percentages. Noting that, of course NbO_2 is six times heavier than carbon, and these carbon materials are rather porous.
- The effect of Nb on the catalysts is not very clearly illustrated, nor is the parameter space. It is unclear what the catalyst parameters to be varied are.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The presentation was very well made by the PI. All the information provided in the presentation was very specific and clear. The charts were easy to read and understand. The team has made excellent progress in the last year. The project has accomplished both small- and large-batch catalyst synthesis at Ford, ORNL, and Exothermics and then characterized the catalysts at the University of Michigan and Northeastern University. The team has also prepared ink using PVD-made catalysts, prepared catalyst-coated membranes (CCMs), and assembled/tested them under polymer electrolyte membrane fuel cell conditions. Some of the team's accomplishments are commendable:
    - The discovery and validation of the use of two targets to achieve higher electrochemical surface area (ECSA) for the catalysts
    - The use of a Ketjenblack carbon black support to achieve a higher catalyst surface area and activity for large-scale production conditions
    - The discovery of the lack of effective Pt-Nb alloying in small-batch catalysts and a small amount of alloying for large-production batch catalysts

  Overall, the project team has had great accomplishments. The team was able to demonstrate a high-performing MEA made using a production lot catalyst from Exothermics (#Exo-180308, on slide 19) with a mass activity of 352 A/gm_{Pt}. Although this mass activity does not meet the DOE's 2020 target, it is nonetheless close.
- The project team demonstrated outstanding progress toward the project's final goal; all interim milestones were passed, and a quite challenging (for a new material class) go/no-go performance was obtained at two testing facilities. Taking into account a number of synthetic difficulties the team had at the beginning of the project, and how quickly they were addressed, the team has a perfect trajectory toward budget period II. All

milestones and go/no-go targets were based on measurable characteristics, either the materials (physical/ chemical) or the final fuel cell performance of Pt-NbO_x/C electrodes, which fully complies with the DOE requirements and allows for a clear estimate of project success.

- The project has meet its Year 1 go/no-go milestone. The project has obtained good activity for a Pt/C catalyst and has been able to improve that activity with an alloy catalyst. Efforts have been focused on obtaining the activity milestone, and the characterization of the samples has been lagging (e.g., the particle size of niobia deposited is not known, Pt location relative to niobia is not known, and ionomer location relative to Pt and niobia is not known). The deposition techniques have not been able to deposit a narrow size distribution of Pt particles. This results in large particles that have poor Pt utilization and small Pt particles that offer high initial catalyst activity and high Pt utilization but are more susceptible to dissolution and have poor durability. The large particle size distribution may make it difficult to achieve the durability and activity targets simultaneously, as the smaller particles needed to make up for the lower mass activity of the large particles are inherently less durable. The inability to produce a smaller particle size distribution could potentially be what limits this approach. The project has had some difficulty in creating alloys, and Co has been formed as an oxide, rather than being incorporated into an alloy, decreasing the benefit of the alloying element and increasing durability concerns.
- A variety of batches have met the DOE performance target in Milestone 3. The large-scale batches are also promising and do not show a loss in performance with scale. There are some questions with respect to why the specific activity varies between sample sets. Some alloying was observed in the PtCo materials but not in Pt-Nb. The PtCo/NbO_x/C specific activities, however, fall within the range of Pt/NbO_x/C values. It is unclear whether alloying has had an effect on performance and what route would further improve activity.
- The durability has not yet been assessed, even though it is a key driver for this research; however, it was stated during the presentation that milestones have been moved forward.
- The project has made progress to date by producing a series of samples to demonstrate the process. The process details still need some improvement, as evidenced by the clustering of particles and sparse areas. The post-characterization is rather valuable, including x-ray photoelectron spectroscopy (XPS), ECSA, and mass activity; more needs to be done. The project has shown mass activities that are quite reasonable, as are ECSAs. However, it is unclear what the role of the NbO_x is; on slide 16, the NbO_x weight percent is only roughly 0.2% to 1.5%. It is likely the team could have obtained the same ECSAs with 0% NbO_x, and possibly the same mass activities. At these low concentrations of NbO_x (even 1.5%, which is still roughly 6% NbO_x by weight, with reference to the carbon material), it seems likely the vast majority of the Pt is deposited onto the carbon support. Slide 17 has higher concentrations of NbO_x; however, no strong correlation between NbO_x percentage and mass activity or ECSA is clear. Thus, in the end, more work is needed to understand the NbO_x coverage and the role it plays in the results.
- Clear progress toward meaningful milestones is made, even if the trends, and an understanding of why this is happening, are not there. There seem to be too many variables to down-select; a focus on one source of PVD is suggested. The use of better proven carbon supports is also suggested.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- The team is composed of very experienced and reputable scientists from academia and industry. Ford and ORNL are very well versed in DOE projects, and the PI, Jim Waldecker, is very experienced in running such projects. The academic, national laboratory, and industry combination of the team is adequate to successfully drive this project.
- The impressive overcoming of initial irreproducibility in catalyst composition is a solid indication of effective team work. All partners participated in the reviewed budget period and contributed to demonstrated accomplishments.
- The project has a good set of partners, and materials are moving between them. Northeastern University and ORNL may stand the best chance at understanding the fundamental interaction between Pt, NbO_x, and carbon.
- The collaborators and roles are clearly presented, along with which partners contributed to each milestone. There are a number of institutions being coordinated in this project, and each provides value.

- Collaborations between Ford, EWII Fuel Cells, ORNL, and Exothermics appear to be going well so far. Collaborations with the National Renewable Energy Laboratory and the Fuel Cell Consortium for Performance and Durability appear to be just getting started.
- There appears to be excellent collaboration in view of meeting milestones, with a shared common sense of urgency.
- The collaboration seems very good, with multiple exchanges and interactions demonstrated.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is very relevant to the MYRDDP. The proposed PVD catalyst development goals are aligned with DOE's 2020 performance targets for electrocatalysts and MEAs for transportation application. The project team's development of a large-scale manufacturing process at Exothermics is expected to meet DOE's cost-effective and high-yield catalyst manufacturing strategy.
- Low-platinum-group-metal with high-platinum-mass-activity stabilized platinum particles for increased durability is a highly relevant area. These types of projects are a major cornerstone of the DOE Hydrogen and Fuel Cells Program (the Program), which could have an impact on the next generation of fuel cell vehicles. This project is exploring a new cathode catalyst powder that has the potential to stabilize platinum particles and reduce carbon corrosion.
- The accomplishment of all technical targets will provide a substantial support to the Program's goals and objectives, especially taking into account that, according to a tech-to-market analysis, the catalyst will be cheaper at scale, with a tremendous potential for higher durability.
- The project addresses catalyst activity, cost, and durability. It supports and advances the Program's goals and objectives.
- The project is relevant and addresses both the cost and durability barriers. The project supports DOE goals and objectives.
- The true benefit of the NbO_x has yet to be demonstrated during the cycling testing. To enhance performance, there is a benefit to the alloy catalyst PtCo, but this (which is already proven) is not the scope of the project. There could be a significant effect on catalysis with support/spillover onto NbO_x.
- While Nb is supposed to help with Pt stability, support stability is not addressed. A shift to better-performing supports should be planned.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Future plans will be mainly targeted to address durability issues and improving MEA performance. The stability and durability protocols recommended by the FCTO (in the MYRDDP) will be used, and the beginning-of-life (BOL)/end-of-life parameters will be benchmarked with previously tested commercial Pt/C catalysts. The detailed characterization planned will build a correlation between the structure of the catalyst and its performance, accelerating the achievement of the final project goal.
- The proposed future work is logical and relevant. The added milestones to address durability are an improvement in the work plan. The planned increased effort in characterization is also appreciated. The proposed future work does not appear to include any effort to narrow the platinum particle size distribution, which is considered a key factor in obtaining both high activity and high durability.
- The proposed future work addresses most barriers; specifically, there will be a focus on durability and materials characterization. Work at high current density may also improve performance at rated power.
- The team clearly understands the shortcomings of the work so far and is planning to address them.
- The team has correctly identified the scope of future work and documented it on slide 24. Durability and mass-transport loss are two of the vital pieces of information needed to determine the feasibility of using PVD-mediated oxygen reduction catalysts in fuel cells. Since the PVD-made catalysts have less alloying,

their stability/durability under start/stop and load/humidity cycling is vital to the success of these catalysts. The start/stop and load/humidity cycling tests should be part of the future work.
- It seems that producing the anticipated materials has been more difficult than expected, hence the backward shift in the testing phase of durability testing. The planned structure is good, but there could be time limitations in having a feedback loop generate incremental improvements in catalyst design.
- All durability measurements are included in future work—this is critical for the success of the project. An understanding of the Pt/NbO_2/C structure to the appropriate detail is missing in the proposed future work section. The coverage of NbO_x on the carbon is unknown, as is how much of the Pt is on the NbO_x and on the carbon, respectively. It is unclear how the carbon pores are affected and how much of the results are due to Pt/NbO_x interactions and to Pt/C, respectively. There is much fundamental understanding of this system that is not being addressed in the future work. These details will help other projects in the future.

Project strengths:

- In terms of technology, the sputtering technology can create unique catalyst structures cost-effectively. The PVD method is being practiced today by many commercial electrode manufacturers. The team has demonstrated the method's feasibility in small- and large-scale methods. The approach of making a single-layer catalyst by sputtering is expected to be more cost-effective than the layer-by-layer sputtering approach. The possibility of efficient recyclability by the PVD process is another strength of the project, as depicted on slide 7. The team consists of a qualified PI and team members with adequate technical experience to drive the project deliverables and pathways.
- A solid team of experienced researchers in the field with specifically adjusted tasks is definitely a strength of this project. All milestones and go/no-go points were met, which, in combination with detailed and well-described future plans, substantially increases the team's chances of meeting DOE targets.
- There is a good set of partners with the potential to successfully execute this project. The project is exploring new materials with a hypothesis on how these materials can improve both performance and durability.
- A variety of materials from this project have met the DOE performance target in Milestone 3. The materials being developed and evaluated have set solid progress for continuing work in a relatively short time.
- There is huge potential in engineering a structure that creates well-linked sites with high activity and good support to reduce side reactions or to assist with oxygen intermediate species.
- This project provides an alternative catalyst preparation method that may provide some manufacturing benefits and cost savings. The niobia may improve durability.
- The project contains a focused concept development with good team integration, as well as a clear understanding of the issues.

Project weaknesses:

- To date, there are no measurements on durability. According the project plan, durability measurements are not supposed to have happened yet; however, when a (the) major result of the project is to increase Pt durability by stabilization, it is hard to evaluate the project until durability measurements are made. The project will (and should) have results by next year. There seems to be a lack of "science" in this project, where science might be tremendously valuable to it. The concentration of effort is more of an Edisonian approach to vary the NbO_x weight percent and Pt weight percent (granted, Ford and Edison were friends, but this approach is unlikely to help other projects), at least at this point in time; it seems unlikely that this approach will provide the ability to fully explain results. NbO_x interactions should be understood, and coverage on the carbon should be examined. Understanding the Pt bonding, as well as the degree to which it is on the carbon or NbO_x, seems critical to being able to explain how the system works.
- The limitation of particle size distribution for PVD-made catalysts, both for small- and large-scale batches, is concerning. The team has to focus on controlling the PVD process to achieve narrower particle size distribution. The shelf life of PVD-made catalysts is not known; an understanding of shelf life is important. The catalyst structure of the PVD catalyst in ink and CCMs should be analyzed to understand its structural stability under ink-making conditions.
- The sheer number of variations almost demands a better grip on operational conditions to composition to performance to durability, and could be more suitable for a combinatorial chemistry approach. Good fuel

cell testing also requires an adjustment of ink recipes to obtain the best performance results, extending the matrix further.
- There are questions as to how durable these materials will be and whether catalyst optimization for durability will have a negative impact on the BOL performance presented. It is also unclear how performance can continue to be improved. Much of the future work and many of the upcoming milestones, however, address any weaknesses.
- To date, the project has lacked appropriate characterization to indicate what the structure produced is and to prove or disprove the hypothesis that niobia improves durability.
- Progress is slow, with inconsistent results leading to an unclear development path, as well as the use of conventional carbon supports.

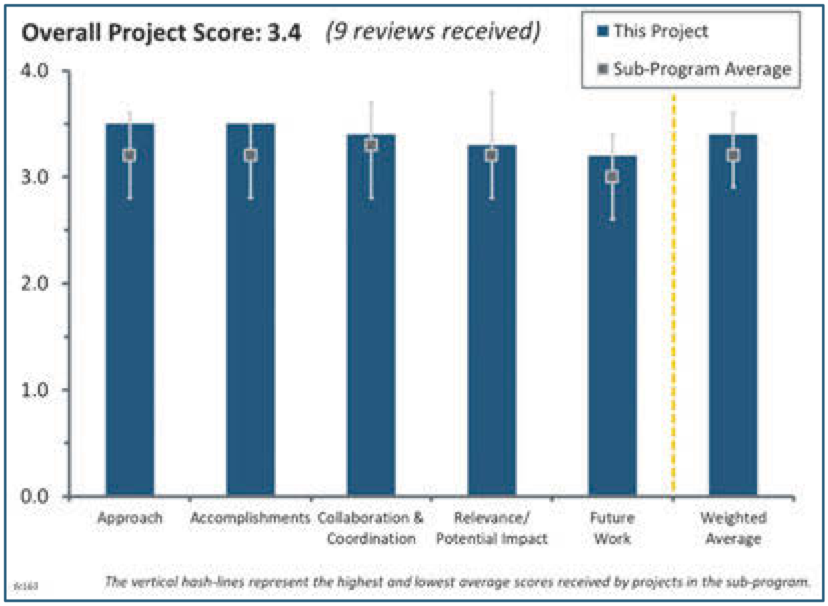
Recommendations for additions/deletions to project scope:

- No changes to the project scope are recommended.
- ORNL has good experience and equipment for thinking a little outside the box on this project scope to anchor sites and gain better control over deposition composition. ORNL team members may thus discover what is really happening in this catalyst system and better understand how this could benefit the goals, and where not. Otherwise, without understanding, the iteration could lead to merely deposition of only more Pt with high surface area, lacking durability.
- More science is necessary; it is important to understand the NbO_x coverage and bonding on carbon and how this affects the carbon porosity. The team needs to understand the Pt bonding and how much is on NbO_x and on carbon, respectively. The Pt bonding interactions should be measured, and durability measurements should be taken (as planned in the future work).
- The following additions will help the project understand the quality of PVD-made catalysts better:
    - Performance stability under load cycling and start/stop cycling
    - Structural stability of the catalyst under the ink-making process
    - Understanding of the shelf life of PVD catalysts
- Work to narrow the particle size distribution could be beneficial.
- The use of state-of-the-art carbon supports is recommended.

Project #FC-163: Fuel Cell Systems Analysis

Brian James; Strategic Analysis, Inc.

Brief Summary of Project:



This project seeks to estimate current and future costs (for years 2020 and 2025) of automotive, bus, and truck fuel cell systems at high manufacturing rates. Analysis projects the impact of technology improvements on system cost, identifies low-cost pathways to achieve U.S. Department of Energy (DOE) automotive fuel cell cost goals, benchmarks fuel cell systems against production vehicle power systems, and identifies fuel cell system cost drivers to help facilitate Fuel Cell Technologies Office programmatic decisions.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project uses an excellent approach to estimate current and future costs of automotive, bus, and truck fuel cells (for years 2020 and 2025) at high manufacturing rates using the Design for Manufacture and Assembly (DFMA) method. Integrating the latest technical achievements and results of other consortia (DOE-funded projects) and industry contacts gives an overall coherence.
- The DFMA method for cost estimation is very good, and the close interaction with component suppliers and system developers is key to fairly accurate cost estimations. The principal investigator (PI) also keeps broadening the scope based on feedback, which is highly appreciated.
- The team uses a proper combination of fundamental models and component and material test validation to perform analyses. The one issue in the past has been the relative unavailability of state-of-the-art electrodes against which to validate, but that issue has been addressed in the past year or more with access to these materials from the Fuel Cell Consortium for Performance and Durability (FC-PAD) and other DOE-funded electrode/membrane-electrode-assembly (MEA) projects.
- The approach of using system analysis to inform DOE about the current status and opportunities for cost reduction is appropriate for this project. Updating the light-duty vehicle (LDV) model annually, while updating medium-duty vehicle (MDV), heavy-duty vehicle (HDV), and bus system models less frequently, makes sense. The DFMA approach has been refined through the many years this team has been conducting cost analyses for DOE.
- Strategic Analysis, Inc. (SA) has provided a consistent approach of DFMA analysis in its bottom-up cost analysis. Occasionally, SA relies on supplier quotes for comparative evaluations (i.e., perfluorosulfonic acid [PFSA] vs. electrospun polyphenylsulfone [PPSU]), which can favorably bias toward the DFMA analysis. SA actively solicits input from projects and manufacturers to ensure the project makes the right assumptions. SA also consults with the U.S. DRIVE Partnership Fuel Cell Technical Team to ensure realistic system assumptions and technology choices.
- SA does about all that can be done to analyze fuel cell systems. The PI and his team use reasonable methods and models to estimate and project costs and volume cost reduction. The team supplements project research with information from the project's national laboratory partners and the literature.

- The project employs a very structured and regularly updated approach to evaluate the high-volume cost of fuel cell systems. The system topologies and stack performance assumptions are updated to meet the state-of-the-art technology status. Recent trends, such as the use of fuel cells for truck applications, are included in the work.
- The approach to performing the work is on target to solve the technical barriers listed.
- The DFMA method seems like a valid approach to address the cost calculation issue. The project has covered many materials and manufacturing technologies; however, the fundamental assumptions leading to the calculated costs are not stated in the presentation. This absence makes it difficult to assess the relevance of the calculated costs.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project showed excellent progress toward identifying the major cost changes year to year. This progress will help DOE achieve its goals by tracking how technology changes increase or decrease cost.
- Validation of the state-of-the-art PtCo-alloy electrode appears strong. Over the past year, the team has performed solid analyses of the high-pressure operation without water vapor transport (WVT) operation, a viable shutdown procedure, and cell voltage cycling mitigation, with a focus on potential impact on system cost. The analysis is sound. There are some questions about the limiting current density assumptions, such as the relative humidity (RH) dependence, but as long as the data is not used far outside the validation regime, there is little concern.
- Most of the work this year involved updating last year's model, but a few new areas were investigated, with useful results. An alternative membrane support based on electrospun PPSU was investigated and found to be significantly less expensive at high volume than the expanded polytetrafluoroethylene (ePTFE) supports used in the prior year's analyses. SA also investigated co-electrospinning of ionomers and supports, as well as electrospinning of catalyst layers. These studies were useful in determining that electrospinning is similar in cost to conventional fabrication methods for these processes. An additional side study on physical vapor deposition (PVD) of platinum catalysts demonstrated that PVD synthesis costs are lower than the cost of traditional wet chemical methods.
- SA did a good job updating estimates and projections based on market trends (changing materials and manufacturing costs) and changes in the technology incorporated in fuel cell systems.
- The regular updates of the cost analysis are achieved on track, based on the available information.
- The project showed good progress on LDV and now MDV/HDV cost estimation.
- The project achieved this year's objectives. Automotive cost adjustment for 2018 and cost estimation for MDV have been achieved, with an expected deliverable for September 2018.
- The defined project goals are met; the overall DOE target of <$40/kW seems achievable for large production volumes for the 2025 auto system.
- SA has made some good progress this year. It was nice to see the team focus on the d-PtCo/HSC (high-surface carbon), which is the most relevant automotive system. There appear to be some discrepancies between the membrane support cost study and the composite membrane costs. It would be good to provide details of all aspects of the process (line speeds, scrap rates, etc.) to understand where the differences lie. It was premature to do a cost study on the PVD catalysts, which have not yet demonstrated decent performance. The medium-duty truck analysis, showing durability requirements leading to higher system costs, was interesting.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- SA has done an excellent job of collaborating with the Argonne National Laboratory (ANL) systems analysis project, as well as with several DOE projects involved with component research and development (R&D). The interaction with an extensive list of vendors who have supplied quotes and technical information is also very useful.

- ANL and SA work very well together to conduct coordinated system and cost analyses to determine the optimal system design to achieve the minimum cost. SA consults with many sources to get input for the project model and to get feedback on the technology options the team considers.
- The ANL team works synergistically with the various DOE projects, both to assist those projects and to feed ANL's own model development. The ANL team also builds on the learnings from FC-PAD and feedback with SA in the cost analysis project, as well as with original equipment manufacturers (OEMs).
- The project has good involvement of industry partners for the cost analysis. As the market is transforming rapidly at the moment, special attention should be paid to also include new players (especially on the balance-of-plant component side regarding hydrogen recirculation, air compression, air filtration, etc.).
- The project team has good cooperation with ANL and the National Renewable Energy Laboratory (NREL) on the analysis and results, and the team has excellent contacts with industry.
- The project partners are well engaged and provide valuable input. Industry and national laboratory partners are well represented.
- SA made good use of their partners' input and the literature; however, the scope of the analysis is narrow and is focusing on—virtually locked onto—PFSA polymer electrolyte membranes (PEMs) using hydrogen/air. Maybe this is what DOE wants; however, it would seem prudent to consider competing fuel cell technologies, such as high-temperature PEMs, alkaline PEMs, etc. to see how using these technologies might affect predicted projects and costs, which could guide the approach to market.
- The project has worked with a large spectrum of companies. However, the major state-of-the-art material suppliers are missing (e.g., W.L. Gore, DuPont, Tanaka Kikinzoku Kogyo K.K., SGL Group). Furthermore, there is no comparison between the calculated cost and the reference market prices of component suppliers to validate the calculated numbers.
- The collaboration with ANL is clear, but the role of NREL is unclear. The PI's discussions with other industry developers is critical.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Because cost reduction is, at the moment, the single most important remaining barrier for the market introduction of fuel cell vehicles, this project is extremely important for identifying the major cost drivers and focusing R&D to reduce overall cost. It is also extremely important to provide decision makers, industry, and the general public with verified information on the cost of fuel cell systems at higher production volumes as a basis for strategic decisions and to provide perspective about how the cost can be reduced when moving from very low-volume production all the way to mass-market production. The work is very valuable, and continuing the analyses is strongly encouraged.
- This project provides the Hydrogen and Fuel Cells Program (the Program) with cost and performance annual updates that serve as the key feedback for assessing the state and progress of the technology and, indirectly, the effectiveness of the Program. This project also serves a valuable role as an independent, public validation/verification of the various project efforts. The project also serves to guide other teams in choosing proper operating conditions and regimes for their development.
- Since the Program defined cost and performance targets delineated in the Multi-Year Research, Development, and Demonstration Plan, it is necessary to track the progress toward hitting these targets as the Program progresses. SA is performing this function and doing it in a reasonable way.
- This project provides a powerful tool to forecast the costs for fuel cell systems. The project uses very recent achievements of other projects, which engenders broad consistency. The project aims to identify fuel cell system cost drivers to help DOE to refine and update its targets.
- Identifying the cost drivers that enable fuel cells to meet their expected performance is highly relevant to help target areas that need more research.
- Cost is a key indicator of any technology; this project helps with understanding the progress in terms of costs.
- The relevance of this project is mostly to provide DOE with status updates on the DOE technology portfolio and occasionally to help guide research priorities. More focus on the latter would be

preferable. Direct value to OEMs and developers is limited because they do their own cost studies. Academic and national laboratory projects can use SA to report the cost potential of their concepts when they do not have their own resources.
- The project is useful for estimating cost status and informing DOE, but it does not significantly contribute to technological improvement.
- When costs are transparent, decision makers can orient more easily. The calculated cost is based on the current status of the system analysis. However, the assumptions for the cost calculation are not always clearly stated so that one can comprehend the calculated costs. Material prices are not clearly marked to indicate whether they represent the market price based on quotes or whether they have been calculated. In the latter case, the market situation is not reflected. This might lead to an incorrect assessment when materials or technologies are directly compared regarding their cost effectiveness.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed inclusion of durability into the cost modeling would be a very important step, especially as applications with different durabilities are being discussed (i.e., passenger vehicles vs. buses and trucks).
- The future work is well planned and logical. The proposed addition of durability considerations would be helpful.
- The project has a good handle on where it needs to go. Durability is a great addition.
- The proposed future work listed by the project team is as expected and in line with the results shown.
- The team will continue with support of the annual cost and performance assessments, which is proper. In addition, the team has been tasked with expanding to MDVs, as directed by DOE. While the team is also strongly linked to and supports FC-PAD, more focus on developing the fundamental knowledge that will allow developers and suppliers to continue to improve performance and durability is desirable. Such tasks would include better understanding of the non-Fickian (local oxygen) transport in the electrode, water transport fundamentals, durability fundamentals, and contaminant mechanisms and mitigation.
- Slide 30 says the future work is to “complete studies and final report,” which is good but somewhat vague. Considering the details presented and that there are three more years of work until September 2021, it seems some direction should be offered for the future work. Many things could change in three years. Part of the future work of SA and its national laboratory partners in analyzing fuel cell systems should be focused on examining the trade literature to see whether there are market forces or technical innovations that could radically alter cost estimates and the projections of system performance and costs.
- All the topics in the LDV future work are justified, especially the updated ionomer cost studies and incorporation of durability into cost modeling. It is desirable for SA to prioritize studies to assess the potential cost of systems containing low-technology-readiness-level (low-TRL) technologies (non-platinum-group-metal [non-PGM] anion-exchange membrane fuel cells [AEMFCs]) to help DOE prioritize research funds.
- The proposed future work seems to address additional technologies that have not been calculated so far. A comparison between calculated costs and forecasts of market prices from suppliers for large industrialized quantities throughout the value chain might provide some useful insights about the validity of the cost calculations.
- The proposed future work aligns with the project plan. A cost model for electrospun electrodes is desirable, in addition to the model for electrospun membranes presented this year.

Project strengths:

- The team has excellent experience in DFMA and cost analysis. Excellent interactions with DOE projects and vendors provide extensive information about design of state-of-the-art fuel cell components and systems.
- The project provides an excellent tool for tracking cost and understanding the impacts of changes.
- Extremely valuable cost analysis provides important feedback to identify and prioritize future R&D to drive down fuel cell system cost.

- The team has a very strong grasp of fuel cell fundamentals and model development and application. The project is a strong collaborative effort with FC-PAD. Recently, the team has had good access to some state-of-the-art materials, which will be more relevant for future mechanistic studies, to better populate the project models.
- The project shows a good assessment of fuel cell performance and costs and cost changes with production volume for fuel cell systems based on favored technologies for making a system.
- The project's strength is its good approach to estimating current and future costs of automotive, bus, and truck fuel cells (for the years 2020 and 2025) at high manufacturing rates using the DFMA method. Integrating the latest technical achievements and results of other consortia and industry contacts engenders broad consistency.
- One key strength is the collaboration with ANL to develop a low-cost system. The project provides high value to DOE in assessing system costs as a function of production volume. The approach of the DFMA methodology is another strength.
- The project has strong collaboration with ANL. The cost is being calculated based on the modeling results of an optimal system. The resulting technical assumptions should provide a good and transparent basis for the cost calculation. The project conducts broad analysis of various materials and manufacturing technologies. The project has employed a stable calculation methodology over the years.
- The PI takes feedback from industry and works closely with industry.

Project weaknesses:

- Perhaps one weakness is the lack of access to a full fuel cell system to validate the system-level model, including dynamic operation and durability. Providing access, however, would require a major development effort, which is outside the scope of this project and, perhaps, of the Program overall. The team adequately addresses this weakness with consultations with the OEMs and other system developers.
- The strength is that SA is doing a good, detailed analysis of favored technologies for making a fuel cell system. The weakness is the technical team members are not seeking out possible disruptive forces or technology changes for SA's projections. Maybe seeking out such forces or changes is out of scope, but it would seem wise to search the trade and technical literature more.
- Project weaknesses include the following:
    - The cost degradation seems based solely on higher utilization of one machine, which has a specific capacity. Typically, in the course of technological advancement, smaller machines are replaced by larger ones. Here, it seems that once the capacity of a machine is reached, the exact same machine is then duplicated. Still, one cannot see any step costs in the cost degressions.
    - The commercial assumptions (mark-ups, location factors, value/supply chain) are not stated in the presentation.
    - No reference to a bill of materials or geometrical design of the cells is given.
    - No validation or disagreement of calculated costs by suppliers is discussed, so the relevance of the calculated cost cannot really be assessed.
- One weakness is the comparison of ePTFE using supplier quotes with electrospun PPSU using DFMA. There are apparent inconsistencies within the membrane cost analyses with different supports.
- The model should also integrate system durability and take into account the impact of "degraded modes" on the performance and cost. Lack of validation of the model is a project weakness.
- As it is set up, the project is not likely to lead to technological improvements. It only demonstrates the current status in terms of cost.
- Systems could be refined further with industry interactions.

Recommendations for additions/deletions to project scope:

- As new suppliers for stack and especially system components are entering the market, the project team should try to include more industry partners in the analysis (e.g., inclusion of additional suppliers for system components such as air compressors and hydrogen recirculation). On the stack side, special focus should be paid to bipolar plate coating and sealing processes. Inclusion of durability would be very important, especially for the commercial trucking applications that require long lifetimes. As the technology is progressing rapidly, the project team is encouraged to continue updating system topology and performance data (e.g., MEA power density). Higher power densities are being observed for laboratory stacks and systems, and it is expected that these higher densities will be reflected also in the next state-of-the-art systems that are being introduced to the market. Also, ways to further reduce system complexity, such as removing the humidifier or using only a compressor instead of a compressor/expander module, should be taken into consideration. Attention should be paid that specific performance targets do not drive up overall system cost (e.g., if 9.5 kW/g_{Pt} requires two-stage charging and might affect overall system efficiency as a result of high parasitic power consumption of the compressor, it might be possible to slightly reduce this requirement to benefit the overall system cost).

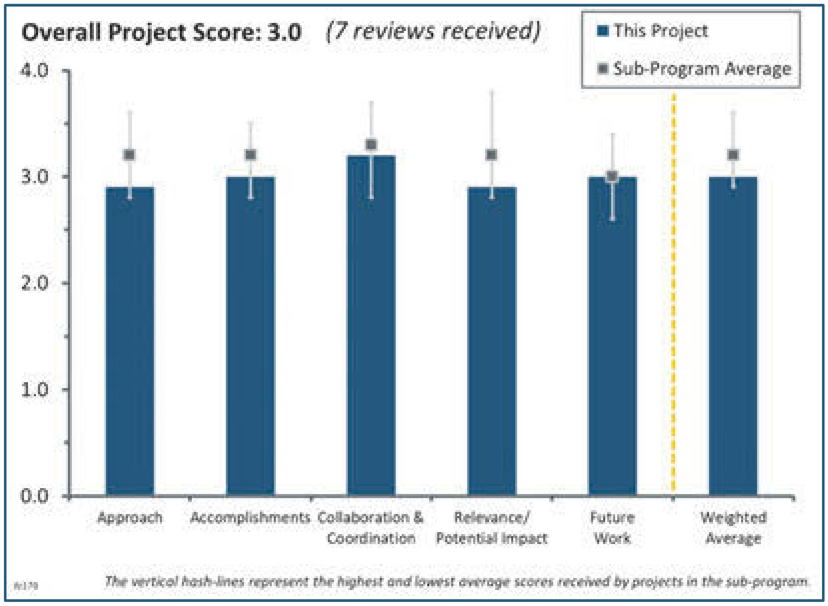
- DOE is investing heavily in low-TRL concepts such as non-PGM catalysts and AEMFCs. SA should run cost analyses (with system support from ANL) to model the cost potential for these systems. These analyses could help define technical targets for these projects. For example, the analyses could show what power density an AEMFC would need to achieve to be cost-competitive with a polymer electrolyte membrane fuel cell (PEMFC) system, considering that the AEMFC system will need a carbon dioxide scrubber and a large humidifier (100% RH in required). Such analysis could also show what power density makes a non-PGM PEMFC cost-competitive with a Pt-based system. SA is uniquely qualified to conduct such analysis, without which it is difficult to justify DOE's investment in these technologies. SA should provide a clear, detailed table for the costs of all the components in the same units (dollars per system or dollars per kilowatt). The team should use Pareto analysis to determine which components warrant R&D for likely cost reduction. The team should revisit seals and gasket costs because SA's current projections are too low.
- Greater focus is recommended on contributing to the fundamental knowledge base, including mechanistic understanding of performance and durability limiters and enablers such as local oxygen transport, water transport, and electrode and membrane degradation and contamination. It would be interesting to see a cathode stoic sensitivity study on cost and performance to address the wide range of stoics shown in various presentations (ranging from about the 1.5 of this project to as high as 2.5) and to focus teams on a more relevant and productive value.
- The team should search trade and technical literature more for alternative or disruptive technology and estimate the cost and performance changes relative to favored technology as a benchmark.
- The model should integrate system durability and take into account the impact of degradations on the performance and cost.
- For the presentation of the cost degression on slide 7 or the waterfall chart on slide 8, a cost breakdown into material cost, manufacturing cost, and mark-up cost would be very helpful.

Project #FC-170: ElectroCat: Durable Manganese-Based Platinum-Group-Metal-Free Catalysts for Polymer Electrolyte Membrane Fuel Cells

Hui Xu; Giner, Inc.

Brief Summary of Project:

The project objective is to develop a Mn-based platinum-group-metal (PGM)-free catalyst and membrane electrode assembly (MEA) as a replacement for current PGM catalysts. The developed catalyst and MEA will have lower cost/cost volatility, improved corrosion performance, improved demetallation performance, and reduced membrane degradation compared to the baseline. The developed catalyst and MEA will be tested on a development fuel cell stack.



Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project approach is appropriate, consisting of material synthesis, characterization, and modeling. Inclusion of durability as a key parameter for design of catalysts adds significant value to the approach.
- The development of effective Mn-based catalysts could reduce MEA costs compared to the current dominant PGM-based catalysts. Hence, the objectives to enhance the performance of Mn-based catalysts via systematic and integrated investigation is very appealing. The team has a well-defined, but possibly too optimistic, pathway toward identifying and producing the desired catalyst materials.
- All project objectives have been clearly identified, and the approach is carefully designed to address all of them.
- The development of Fe-free catalysts has been a key need. The inclusion of computational work is good, but the work seems lacking in rigor and relevance. The synthesis work is very promising, even while details are lacking. Comparison to Fe-based systems is needed. In addition, the inclusion of and reliance on MEA results is good.
- Giner, Inc., will address the U.S. Department of Energy mission on development of PGM-free oxygen reduction reaction (ORR) catalysts, which should have intrinsic activity similar to state-of-the-art Pt/C (at low loadings). The technical targets the project will achieve by the end of funding period are performance-based (>0.044 A/cm^2 at 0.9 V).
    - Despite the project's being specifically dedicated to catalyst durability, the final measurable durability targets were not clear. It is unclear whether the plan is to improve durability by 50% at all Multi-Year Research, Development, and Demonstration Plan design points (potential cycling and carbon corrosion).
    - The demonstration of rotating disk electrode (RDE) data with ORR performance of Pt/C, FeNC, and MnNC (probably in acidic electrolyte) is a weak argument for Mn catalysts' potential 50% higher stability. The carbon produced during pyrolysis in the case of Mn will be less graphitic (Mn does not promote graphitization), and carbon corrosion will be more pronounced for Mn-N-C catalysts.
    - The technical approach is based on initial density functional theory (DFT) calculations, which will be used for the synthesis of MnNC catalysts, followed by scaling up, MEA fabrication, testing,

and finally validation by the original equipment manufacturer team member. Despite the fact that Task 1 (ab initio calculations) will be performed for all 36 months, Tasks 2, 3 and 4 are weakly connected to the expected results of these DFT modeling studies.

- While finding alternatives to Fe-based PGM-free catalysts is not without merit, first demonstrating that current Fe-based PGM-free catalysts actually do cause increased membrane degradation seems prudent. This does not mean simply stating that Fe is a Fenton's catalyst but rather providing direct experimental evidence that state-of-the-art Fe-based catalysts result in MEA degradation. In addition, based on the technological maturity of this catalyst, the "cost analysis" to be performed by General Motors (GM) seems a little premature. However, if the cost model is supplied at the end of the project, this could be of use to more mature PGM-free catalysts. (It seems likely the model will show that no PGM-free catalyst is yet cost-effective at the stack/system level because of low performance/durability.)
- The project is focused on development of a durable non-PGM catalyst that exceeds the durability of Fe-based non-PGM catalysts. Although the project objectives and critical barriers are clearly identified, they are not clearly addressed. The project design is based on theory predictions that Mn-based catalysts are more durable vs. Fe-based catalysts. However, this theoretical prediction was not clearly communicated. Another flaw in the project design is that the catalyst with lower activity (MnN_4 vs. FeN_4) is selected for investigation.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team has made good progress in development of new Mn-based catalysts with improved activity and, more importantly, improved durability in RDE testing. Additional durability testing in MEAs is critical and appears to be part of the second year of work. The modeling has appeared to result in identification of potentially preferred active sites, and characterization (both electrochemical and physical) appears to be providing good insight.
- Progress across the project has been very good, with identification and initial testing of two possible Mn-based configurations.
- Significant progress has been made during the last year. The principal investigator (PI) has coordinated all efforts with the collaborators well and has managed to execute a number of structural and electrochemical tests for Mn-based PGM-free catalysts. The projected milestone in this year was met, and the go/no-go decision point of 10 mA/cm^2 was exceeded. The project seems to be redundant in light of ongoing Electrocatalysis Consortium (ElectroCat) activities and combinatorial screening of PGM-free systems. For that reason, the approach to focus exclusively on Mn-based PGM-free system is not well justified.
- The computational work is lacking. Recreating previous work and not doing so better, or with more rigor, begs the question of what the stabilities of the different sites are.
    - The following are also unclear: why C14 is "promising"; how these materials and structure compare to Fe, which has been proven best so far; and whether multilayer structures were checked for all, or C10 was calculated in multilayers to allow CN_5C_{10} to form.
    - The synthesis work is interesting, with many materials made, but the connection between the raw materials, processing, and results is very unclear from the data presented.
    - In addition, some very high peroxide levels are seen (example on slide 10), and since Mn is a peroxide scavenger, it is unclear whether this is a mixed H_2/H_2O_2 fuel cell. If so, it seems that the peroxide would corrode the carbon catalyst locally.
    - There is another big question about the purity of the Mn, i.e., whether any Fe is present. Inductively coupled plasma of the precursor salts and analysis of the catalysts for Fe is needed. The inclusion of 0.7 V and 0.8 V holds on slide 12 is great, but it is unclear why the degradation paths are different. This suggests that the currents are so low that the percent plotted is deceiving as to catalyst instability. This low stability is suggestive of unstable active sites or possible peroxide-caused corrosion, which needs to be addressed.
    - While having MEA work is great, the results so far are quite strange, with rapid drop-off at high potential that is suggestive of either a need for ionomer–carbon ratio and electrode structure improvement, or catalyst instability masked by polarization. Hold tests at different partial

    pressures, at 0.65 V, are needed. In general, the team should be more careful in drawing conclusions. This is nice work.

- Significant progress has been made toward using modeling to identify Mn-containing active sites. A significant improvement in synthesis was achieved that allowed the introduction of more active sites, as indicated by results of RDE tests.
    - There were not many accomplishments in terms of durability demonstrated during of constant potential hold experiments, as potential cycling was required every 20 hours to refresh the surface.
    - There is no clear evidence that the Mn-based catalyst performs better than Fe-based in terms of hydrogen peroxide generation, because RRDE experiments were performed on thick films with a loading of 0.8 mg/cm^2. There were not many accomplishments in terms of fuel cell performance demonstrated, and no clear path for its improvement was proposed.
- The performed work according to the statement of project objectives was reported. The role of DFT calculations in achievement of the project and DOE goals is unclear. The interpretation of results (summarized in Milestones 1.1 and 1.2 [M.1.1 and M.1.2]) is incorrect and generic. The structures in M.1.2 were not predicted; these structures have a convergence minimum according to input parameters in the WASP code, while geometries were proposed and used as initial coordinates input. The achievement of the M.1.1 goal on "key descriptors" is irrelevant to project targets and does not have scientific value. These descriptors are used for calculation of reaction pathways for more than 30 years, and Professor Norskov has comprehensively used them for ORR DFT calculations since 1993. Despite the DFT-predicted very specific configurations of Mn-N active centers with exact numbers of N- and C- atoms, the synthetic approach selected is generic, with no ability to precisely control formation of required structural fragments. The statement that introduction of extra Mn ions will increase performance is incorrect unless there is experimental evidence that all Mn atoms will be utilized in the Mn-N active centers. The series of experiments with extra Mn addition and correlation with improved performance should be carefully re-evaluated. The team did not take into account that zeolitic imidazolate framework (ZIF)-8 and all Mn precursors have substantial amounts of Fe. According to the certificate of analysis on ZIF-8, it may have up to 0.1 wt.% of Fe. Manganese nitrates and acetates can have up to 2 wt.% of Fe. The dramatic increase of Mn precursors up to 20 wt.% in combination with ZIF-8 results in the formation of Fe-N centers, which provide the ORR activity. Several studies on this subject are available. The rotating ring disk electrode (RRDE) clearly indicates the presence of H_2O_2, despite the highest loading of catalyst ever reported (0.8 mg/cm^2, while the community standard is 0.6 mg/cm^2), which means MnNC catalysts are not selective in the 4e$^-$ reaction and intrinsically have low mass activity.
- Performance/activity remains a large concern. Additionally, while it is stated that the catalyst shows enhanced stability versus Fe-NC, the end-of-test performance looks essentially the same. Thus, a large focus on improving catalyst activity is still required. However, it is not clear how the team will achieve the necessary activity improvements. The main approach appears to be increasing Mn doping. However, drawing from knowledge of the Fe-based PGM-free catalysts, it appears this approach is somewhat risky (maintaining decent Mn dispersion will be challenging). If this (somewhat) risky approach fails, it is unclear what the backup plan is.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- The presented results indicated very good cooperation among the partners and significant supporting work performed by five national laboratories through ElectroCat.
- Team members have planned and scheduled meetings well, and the PI manages the project effectively. The established collaboration with ElectroCat facilitates the understanding of ORR activity in this class of catalysts.
- Good collaboration is evident, but more feedback between DFT and synthesis, catalyst structure, and MEA will be better.
- Collaboration between the participants is very well coordinated.
- This is a well-coordinated effort between industry and academia.
- Overall, collaboration appears appropriate. One question is whether the modeling results are being used to guide the material synthesis toward designing catalysts with preferred active sites.

- The partners are well engaged and are working with ElectroCat members. GM currently does not appear to be highly engaged in the project, but that is understandable at this stage of the work. Hopefully GM's electrode design work can help to overcome the very low MEA performance.

Question 4: Relevance/potential impact

This project was rated **2.9** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The proposed technology may have an impact on the DOE Hydrogen and Fuel Cells Program (the Program) mission if it will be carefully re-evaluated.
- The project does provide an alternative to the more conventional Fe-based PGM-free catalysts. However, there does not appear to be sufficient evidence that activity/performance can be improved to the required levels, and even if that occurs, there still does not appear to be any evidence that replacing Fe is necessary (it may be, but currently, it is just an assumption).
- Overall, the project is relevant to addressing the primary cost, durability, and performance barriers for fuel cells. It is unclear whether non-PGM catalysts will ever be durable enough for commercial viability. Demetallization and carbon corrosion may be intractable issues. These concerns are not reflective of the work done in this project specifically, but the field needs to reconcile this for the non-PGM approach to have significant potential impact over the next decade.
- Providing the current studies can demonstrate sufficient durability of one or more of the Mn-catalyst configurations, this project would prove very useful to providing lower-cost MEAs and potentially fuel cell systems. However, several aspects on stabilities during operation seem more or less problematic. Hence, there remains an issue as to whether these catalysts can deliver as promised.
- To be focused just on the system with Mn does not look like a compelling case for the project, even though the work itself has been executed in excellent manner. For that reason, it would be difficult to predict that this project, which is focused on the Mn-based carbon catalyst, would make a significant impact on the Program.
- The move away from Fe to Mn in the project is very important, but greater care should be taken to achieve relevant performance tests.
- Although the project is relevant to DOE goals on durability and cost reduction of a fuel cell catalyst, multiple problems with performance and durability at the initial stage of the project make the potential impact of this project unlikely to be high.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work is well aligned with meeting project objectives. Giner, Inc., should consider increased focus on MEA-level durability assessments, including potential cycling and support stability, to demonstrate improved durability in relevant environments rather than RDE.
- The tasks outlined in the future work plan appear reasonable and should allow for the necessary demonstration that Mn-based catalysts could be viable non-PGM catalysts on MEA devices.
- Future work is in line with ongoing activities, and it is well planned.
- The DFT part of the project is questionable. The results of calculations cannot be used as a feedback on catalyst preparation because of the fundamental lack of control of the atomic structure in high-temperature synthesis. The proposed action items on catalyst synthesis and MEA design are relevant to the project goals.
- The future work is not explicit enough to evaluate, especially in the modeling section. Key recommendations are more rigorous structure stability versus reaction pathway comparison, testing for Fe contamination, more rigorous RDE and MEA tests, and diagnostic tests such as stability at different fluxes at the same potential to determine active site stability and turnover frequency.
- Project plans contribute to overcoming some barriers but lack specificity.

- The performance at the MEA level is concerning. The performance is due to either very poor catalyst activity or poor electrode design. The team members should attempt to make an MEA using a state-of-the-art Fe-based PGM-free catalyst to help clarify how much of the gap is from the project catalyst versus catalyst layer design. If the catalyst is the problem, all efforts should be focused on improving activity, as it is currently far too low.

Project strengths:

- Synthesis, characterization, and electrochemical evaluations in RDE and MEA are very well executed. The modeling part is a world-class science, and the PI who did that part should be praised for this work.
- The project team has an appropriate balance of modeling, synthesis, and characterization. The approach has led to identification of a catalyst with potentially higher durability than the incumbent, based on RDE testing.
- There is a strong modeling component in the project. This is a very strong team of experts in modeling, synthesis, catalyst, and fuel cell testing.
- This appears to be a well-balanced and -integrated study focused on improving the performance and durability of Mn-based catalysts for MEAs. The capabilities of partners and collaborators seem to be fully utilized.
- This project provides an alternative to conventional Fe-based catalysts. There are strong team members with different skill sets.
- The shift to Mn-based catalysts is great, and good progress was demonstrated.
- In general, Mn active centers can be used as heterogeneous hydrogen peroxide scavengers.

Project weaknesses:

- The main weakness of the project is significant disintegration between the proposed tasks, milestones, and go/no-go decision points. Tasks are not logically connected, and results of milestones do not effect progress toward project goals. As an example, up to now the project did not benefit from DFT calculations.
  - Another broken link is in the task on catalyst optimization with increase of Mn content. It was reported that RDE evaluation confirmed better performance, per the volcano plot (20% is better than 30% and 10%). However, future work proposes again to increase Mn content. Perhaps this means that 20% is not better than 30%, as presented in the 2018 Annual Merit Review (AMR) report.
  - The unawareness of recent literature on PGM-free ORR catalyst development (which has new trends compared to 2015–2017 hypotheses) is unacceptable for participants in such an important DOE mission project. Recent publications from Norskov, Shuhui Sun, Zelenay, and Banham have exceptionally good information that will help the PI and team to rebuild the project.
- The project design is based on DFT modeling, which does not take into account the real fuel cell environment, such as the presence of water molecules on the surface and potential. So far, DFT modeling has succeeded mostly in interpreting experimental results rather than in predicting new catalysts.
- Evidence for the need to use Mn-based PGM-free catalysts is somewhat lacking. While Fe is a Fenton's catalyst, it is still unclear whether Fe in current Fe-based PGM-free catalysts really causes increased degradation. The MEA performance of the Mn-based catalyst is concerningly low. Significant improvements are required in the coming months.
- Additional focus should be placed on assessing durability (potential cycling, carbon corrosion) in the MEA to determine the feasibility of the approach for commercial applications.
- The computational portion contribution, rigor, and ability to predict are unclear. Since stability and intrinsic performance for Mn systems is unknown, there should be a better effort on this side of things.
- This project has ambitious goals and a substantial breadth of materials options to investigate in a rather limited period of time. The probability of undesirable reactions of the Mn species still seems quite high.

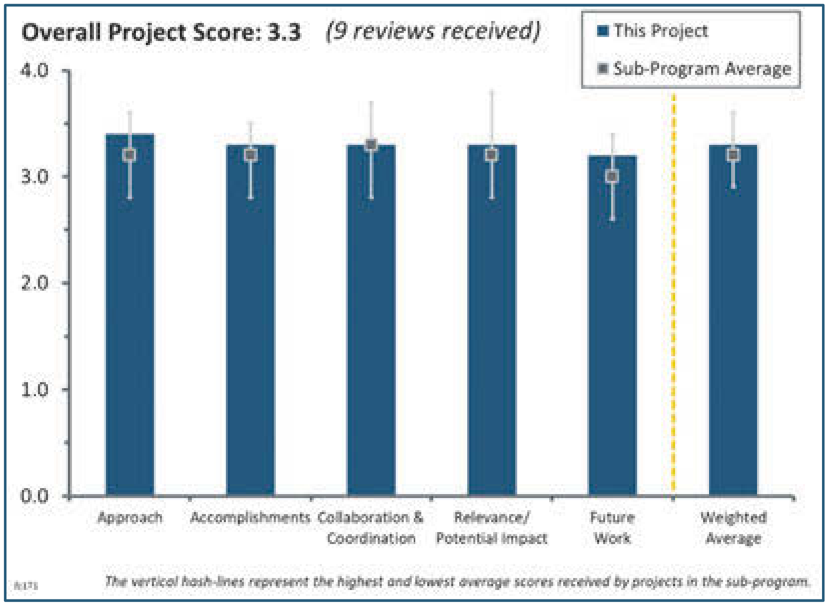
Recommendations for additions/deletions to project scope:

- The team should be allowed to continue pursuing the directions and tasks as described during this AMR report. However, it is recommended that a detailed review of status be performed with all members and key collaborators by December 2018. This would allow for a thorough evaluation of how the materials and test devices actually behave. Then the team can down-select to the one or two very best candidates during the remainder of the second year of this project.
- Additional focus should be placed on assessing durability (potential cycling, carbon corrosion) in the MEA to determine the feasibility of the approach for commercial applications.
- If possible, the reasons for fast catalyst degradation at constant potential RDE tests need to be identified and addressed.
- Better baseline testing would be helpful (perhaps Los Alamos National Laboratory can share its Fe-based PGM-free catalyst).
- A shift to methods that do not rely on a metal–organic framework should be considered.
- It is recommended that the project expand the scope toward more diverse PGM systems.

Project #FC-171: ElectroCat: Advanced Platinum-Group-Metal-Free Cathode Engineering for High Power Density and Durability

Shawn Litster; Carnegie Mellon University

Brief Summary of Project:



This project is developing platinum-group-metal (PGM)-free oxygen reduction reaction (ORR) catalysts for polymer electrolyte membrane (PEM) fuel cell cathodes. A thorough approach that combines advanced, atomically dispersed metal–organic-framework (MOF)-derived Fe-N-C catalysts, PGM-free specific cathode architectures, and advanced ionomers is being undertaken. This project seeks to (1) enable high-power density and improve durability with new cathode structures designed specifically for PGM-free catalysts; (2) increase PGM-free catalyst activity and stability through novel synthesis approaches, including using a simplified, low-cost method; (3) mitigate PGM-free cathode flooding for fast oxygen transport across thick electrodes; and (4) integrate advanced ionomers into the electrode structure for optimal performance and durability.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project appears well constructed, and the strengths of each team member appear to be well utilized. The modeling and experimental work are highly complementary to each other and clearly well-thought-out. Relevant accelerated stress tests (ASTs) are being used.
- The approach of the project is based on re-design of the cathodic catalyst layer (PGM-free oxygen reduction reaction materials) to improve overall fuel cell performance. The approach itself and objectives are clearly described. The main barrier to obtaining higher performance was identified as mass transfer losses, and a mitigation scenario was proposed.
- The presentation was well organized and comprehensively described the various technical efforts under way to address the project milestones shown at the start of the presentation. The various scientific advances and efforts appear to be contributing to the overall membrane electrode assembly (MEA)-based project milestones. Use of MEA modeling is a nice guide for the various efforts, in terms of assessing their impacts.
- The project applies the approaches developed by the investigators from previously funded DOE projects. The approach is sound and helpful in improving understanding of catalyst and MEA development in this field.
- The approach to improving high current density (HCD) is rational. Use of tomography, other characterization, and validation with MOF building blocks seems promising.
- The approach is outstanding, combining synthesis, characterization, and modeling.
- A state-of-the-art (SOA) PGM-free catalyst was received and used to demonstrate performance. The catalyst is then developed and the batch size scaled up to larger batches for catalyst layer and MEA development. This is a very complicated process that could have benefitted from strong technology transfer from the original developer.

- The team's approach of leveraging modeling insights to improve MEA performance is a strong point of this project. A weakness is that the approach is focused mostly on the highest-activity PGM-free materials but these materials seem to be inherently unstable under typical operating conditions. Based on initial results, it seems likely that the project will result in a high-performance PGM-free MEA, but the durability will be as poor as that of previous high-performing PGM-free MEAs.
- The approach seems to be proper to solve the mass transfer overpotential issue with the PGM-free cathode catalyst layer. Water management is a significant issue.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has an excellent start with the accomplishment of milestones so far. Excellent catalysts are available with interesting properties (Fe-free, single-step process) compared to others in the field, and there are new synthesis approaches. Challenges of transport are clearly identified.
- It has been less than a year since the project started, but the project has made good progress and is mostly on track. It is good to see some durability work. More work in this area is encouraged.
- The project has a good start, thanks to the early involvement of a number of investigators from previously funded DOE projects. The results are promising.
- The goals of the project align well with those of the Electrocatalysis Consortium (ElectroCat). The project is on track, considering the first go/no-go is not until September and the team is within reach of those targets.
- The strong focus on catalyst layer design improvements is highly encouraging. In particular, the focus on new methods to deal with water removal in these relatively thick PGM-free catalyst layers will be of use to all PGM-free researchers. While there are concerns about Fe, the concerns amount to one of the least pressing issues at this time. Also, the ionomer work will be critical, but the initial results are rather confusing. It is unclear why the electrode conductivity shows no dependence on ionomer equivalent weight.
- Technical milestones were clearly presented, and progress against those milestones was described well. A challenge is that the stretch goal for the end of the project (450 mW/cm^2) is still >2x below the PGM baseline, so even if the stretch goal is reached, it is not clear whether additional work would then be justified.
- This project has met the initial half-wave-potential goal of 0.87 V vs. the reversible hydrogen electrode, but the power produced is well behind that shown by other developers. The project appears to be falling behind schedule, which puts further targets and the go/no-go decision in jeopardy.
- The project is mainly on track, according to the schedule. However, current density at 0.9 V is still far away from the milestone and first go/no-go review target.
- The project identified sensitivity for hydrophobicity.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- Key personnel are qualified, as demonstrated by their publications on work in this and related fields, but they need to reach out to teams that are further along in the development of this type of catalyst, such as ElectroCat and the Energy Materials Network (EMN) consortium members (national laboratories). The proposal clearly and completely defines the roles and contributions of each team member; the final team, facilities, and equipment required to complete this project are fully in place, ready, and available. This project has full commitment from the partners' senior management and corporate officers.
- The project is well managed, and multiple collaborations, including ones with ElectroCat and EMN consortia, were established.
- The project partners all bring different expertise and have all been integrated well into the overall project. The project should engage more with the National Renewable Energy Laboratory and Los Alamos National Laboratory to understand the ionomer results a little better.

- The collaboration with the University at Buffalo is excellent, and there is some collaboration with 3M. It is not clear how Giner, Inc. (Giner) fits in just yet—whether scale-up is planned or accomplished.
- The team is strong and includes investigators with good electrocatalysis and engineering backgrounds.
- It appears the project is well managed, and the various efforts are well integrated.
- Collaboration is good. The role of each partner is clear.
- The team has complementary capabilities, and the members appear to work well together. One concern is that, other than Dr. Litster's work and switching Mn for Fe, it is not clear how different this project is from the Giner-led ElectroCat project. The work may be overlapping. It is okay if the project leverages that work, but the team should make it clearer that the two projects are not being funded to do the same work.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Increasing overall PGM-free catalyst performance by a factor of four will have a dramatic impact on the entire Hydrogen and Fuel Cells Program (the Program). The new generation of electrodes will be considered a genuine and inexpensive substitute for platinum at the cathode.
- A PGM-free catalyst is critically important for commercializing fuel cells. Fe-doped MOFs have shown significant progress, and additional performance and stability improvements are required. Focusing on water management and other mass transport issues will provide significant benefits for this technology.
- The project strikes an excellent balance between catalyst development, catalyst layer modeling, and catalyst layer design. Thus, while challenging targets have been set, this project is well positioned to close remaining gaps in performance and durability.
- A PGM-free catalyst with improved activity and durability will lead to fundamental changes in the fuel cell industry.
- This project addresses long-standing issues in transport limitations of proton motive force electrodes, including problems with hydrophilicity and ionomer utilization.
- The project is clearly aligned with the "PGM-free cathode" goal for the Fuel Cell Technologies Office, but a concern is whether reaching the stretch performance goal would truly challenge the SOA, because the target performance is still well below the PGM value. Perhaps the technology could be more relevant for stationary applications in which power density is less of an issue. However, a lower power density will drive up cost in components (membranes, plates, etc.).
- It is too early in the PGM-free catalyst area to see a perspective for automotive application. The effort to improve mass transport loss is relevant to general objectives.
- The goals of the project are relevant to DOE goals for ElectroCat. The potential impact is a concern, as it is not clear whether the approach is novel enough to substantially improve durability issues.
- As the iron-based M-N-C catalyst is unstable and has insufficient volumetric activity, it is unclear whether the learning and development on HCD from this project will ultimately be of any value.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work all appears reasonable and well justified by the milestones.
- Future activity is well planned and justified.
- The proposed direction is suitable for research in this area.
- The team needs to address durability, which is the plan for next year. It would be good to see progress toward this in next year's presentation.
- One of the largest (catalyst-level) challenges for PGM-free catalysts is to increase site density. Thus, a strong focus should be placed on demonstrating that active site density can be increased without compromising turnover frequency.
- Introducing higher-stability carbons is a good idea, but the project could experiment with carbonization of the existing catalyst (if that has not already been done). Reporting measured active site density and how

that varies with synthesis parameters would help with understanding activity enhancements. The mesomorphology of the catalyst particles should be understood through adsorption and intrusion studies. The mesoporosity is likely quite low. The project should explain why a particle size of 100 nm is optimum. Dramatically reduced particle size, perhaps below 50 µm, should improve ionomer coverage and utilization.
- In future work, the investigators need to reach out to teams that are further along in the development of this type of catalyst, such as ElectroCat and EMN consortium members (national laboratories).
- A more specific idea to improve water management is necessary.
- The project has just started, and there is much left to be done.

Project strengths:

- The presentation was well organized and clear. The team appears well organized. Technical milestones are clear, and progress appears to be honestly assessed against those milestones. There are nice technical highlights.
- The project will develop a predictive method on integration of PGM-free catalysts into the MEAs. Suppressing the flooding will achieve a significant increase in activity of these MEAs.
- The project has a strong team with complementary capabilities. The principal investigator's modeling knowledge can be applied to develop higher-performing MEAs with these PGM-free catalysts.
- The project team is strong in synthesis, scale-up, characterization, and modeling. The project has good integration with ElectroCat and excellent plans for future improvements.
- The project has strong partners and a good balance of catalyst synthesis, catalyst layer modeling, and catalyst layer design.
- This project group is very experienced in scale-up of laboratory processes and in MEA development and fabrication.
- A strength of this project is the ability to analyze the structure of the cathode catalyst layer, including its hydrophobicity nature.
- The project has a very good start.

Project weaknesses:

- There are minor weaknesses: (1) further characterization of the catalyst layers would be helpful (performance at various relative humidities); and (2) while the modeling work was well explained, further insight into the experimental results would be helpful, e.g., the impact of the ionomer, the proposed mechanism of degradation (the team observed no change in cyclic voltammetry before or after the AST, and flooding was ruled out, so it is unclear why the MEA is losing performance), etc. A stronger focus/path toward increasing active site density is required.
- The only high-level concern is whether, if the stretch goal is reached, that is enough to change the thinking about what is possible with PGM-free cathodes and to justify future work and funding, given the lower power density, thicker electrodes, etc.
- A mesoscale focus is needed, through characterization of catalyst morphology at that level. This team is very capable of addressing this issue.
- There appear to be a number of investigators involved in more than one project in the same research area of the Program. A clear separation of focus and resources is needed.
- It is possible that the materials on which the team is focused will have poor durability. It is not convincing that the Fe-N-C materials will be made stable simply by modifying the carbon.
- This project needs to develop and strengthen the technology base for the Fe-doped MOF-based catalyst.

Recommendations for additions/deletions to project scope:

- The scope is appropriate.
- As durability and deactivation mechanisms become more apparent through ongoing ElectroCat projects, the team may need to modify the catalyst compositions being examined, including focusing on non-Fe catalysts or other modifications.

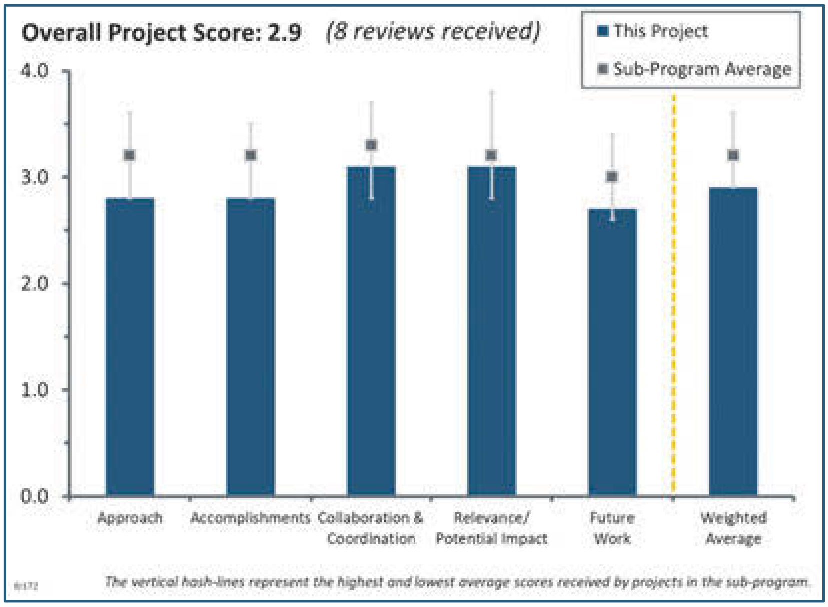
- The recommendation is to focus more on knowledge development in terms of structural implications for mass transport overpotential rather than developmental efforts to achieve the target. This is long-term research; an instant accomplishment would not be expected.

Project #FC-172: ElectroCat: Highly Active and Durable Platinum-Group-Metal-Free Oxygen Reduction Reaction Electrocatalysts through the Synergy of Active Sites

Yuyan Shao; Pacific Northwest National Laboratory

Brief Summary of Project:

The project objective is to improve the activity and durability of platinum-group-metal-free (PGM-free) oxygen reduction reaction (ORR) catalysts through dual-active sites for enhanced oxygen reduction and hydrogen peroxide (H_2O_2) decomposition. Materials and synthesis innovations include (1) dual active sites for ORR and H_2O_2 and (2) thermal shock activation for high activity through increased active site density. The developed catalysts will lower cost, reduce H_2O_2 formation by 50%, maintain the activity level, and double the durability compared to baseline platinum catalysts.



Question 1: Approach to performing the work

This project was rated **2.8** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project team is focused on identifying pathways to produce catalysts using a thermal shock activation technique. This project's focus is to cut H_2O_2 formation by half (versus Pt catalysts), while maintaining the same activity and doubling the durability compared to the baseline. The scale-up of the shock activation technique was not demonstrated.
- Thermal shock activation "freezing" N in a non-equilibrium state is an interesting idea that has been previously explored by others, although not with a duration as short as this project.
- The approach is based on a two-stage ORR assumption, and it is well understood. Thermal shock activation should be described and hypothesized clearly.
- The goals of the project align well with the ElectroCat Consortium (ElectroCat) mission. It is realistic to think that peroxide formation is a source of deactivation in these materials. The approach the team is pursuing is a logical way to address the peroxide formation. While the approach is logical, it is a concern that the initial results do not clearly show that the peroxide decomposer solves long-term degradation in a membrane electrode assembly (MEA). Even if the initial MEA performance was poor, the team should show a clear side-by-side comparison of MEA degradation for the project approach, versus the standard catalyst without peroxide decomposer, to see if the decomposer makes a significant impact in the real-world environment. The project team showed rotating disk electrode results, but a simple MEA test would have been much more convincing.
- Objectives and barriers, in terms of the catalyst design and performance, are well defined. The importance of "Thermal shock activation for high activity by increasing active site density" needs to be more clearly described; it is unclear why this approach is important and what its effect will be.
- The incorporation of two different types of active sites with different functionalities, thereby pushing activity and durability, is promising, but it is not a new idea. If successful, it could dramatically improve the durability of non-PGM ORR catalysts. However, based on the presentation, it is unclear how the current proposed work will be successful. The current limitation is the efficient dispersal and integration of two

different types of active sites into a single catalyst. At this point, the project team has simply mixed particles of the two different types of catalysts and observed modest success. In the future work, the team proposes a molecular-level integration of the dual active sites; however, no feasible methodology for accomplishing this is presented. All proposed future work is a bit vague. To this point, the group has used the standard pyrolyzed metal–organic framework (MOF) catalysts presented and developed by other groups. However, the project's activity is far below that of other groups. Before going any further, the team should rectify this difference to attain reasonable ORR activities. Electrically induced thermal shock is proposed to aid the retention of a higher nitrogen content. While it is a nice idea, it does not seem to be practically feasible. Not only is there no clear link to the rate of thermal treatment and nitrogen retention, but it is likely that the proper removal of Zn, which is required for material porosity and to attain high activity, is not possible with this technique. The project team should move on to a different synthesis process and drop thermal shock from the project.

- The approach advantages, differentiation, and risk mitigation are not clear. It appears that the main differentiators are the incorporation of peroxide scavengers/decomposers to deal with low selectivity of PGM-free catalysts and rapid heating/cooling to "thermally" lock active sites. There are fundamental problems with both approaches:
    - It is not demonstrated that peroxide decomposition will protect the active sites, ionomer, and membrane sufficiently.
    - There is very little proof, if any, that thermal shock is a viable approach. Rather, the fundamental approach of trying for rapid heating, a kinetic bypass of more a thermodynamically active site formation, in the hopes of achieving a thermodynamically unstable and possibly more active site, is problematic, since this is not a durable catalyst. The latter is a really flawed approach.
- The approach is poorly described, raising multiple questions about the selection process for these tasks.

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Catalysts with Fe and Co were identified as most active (this is well known from literature), and two H_2O_2 scavengers were selected. Taking into account that CeO_x is widely used by original equipment manufacturers on the cathode side, tantalum-doped oxide can potentially be of interest for improving electrode durability.
- Two effective hydrogen peroxide composers were identified.
- The project has a good start.
- The project is hitting the milestones, as defined, with the exception of the thermal shock approach (which may not be relevant to the project anyway). The absolute E1/2 should be used in future milestones, as using E1/2 versus Pt/C leads to ambiguity. The Pt/C E1/2 can be different for various catalysts and is known to be lower in sulfuric acid than in perchloric acid.
- The project team has demonstrated satisfactory progress and has at least shown some positive preliminary evidence of the utility of the dual-site catalyst. The researchers have accomplished some of their early milestones, but it is clear that they are still far away from their proposed go/no-go for Year 1.
- The project has made good progress toward catalyst synthesis and the demonstration of the peroxide sweeping effect. Initial demonstration of the thermal shock approach was not convincing and needs to be accomplished quickly or dropped.
- The team needs to confirm the atomic dispersion of metal, specifically Fe, in the Fe-N_4 structure. Fe nanoparticles are not strongly bonded to carbon. The performance of the atomically dispersed Fe catalyst meets the milestone (ΔE1/2 <65 mV versus Pt). MEA performance needs improvement (for both hydrogen–oxygen and hydrogen–air).
- While the project team is meeting some milestones, the project is behind on the more meaningful ones—thermal shock and even the catalyst development and scavenger milestones are lagging in momentum. The new materials made so far are both replicating others' approaches and performing poorly: P9 E1/2 <0.65 using zeolitic imidazolate framework (ZIF) materials is 150+ mV lower than several other groups, and 3.5% peroxide on the one catalyst with E1/2~0.8 (p10) is a huge peroxide level. The peroxide scavenging of Ta and Ce on slide 12 is clearly not meaningful for Ta and is only mildly effective for Ce. Similarly, on

slide 14, the Fe and Co Ta system peroxide reduction is questionable. Effective peroxide scavengers are well known in Pt systems, so it is unclear why new ones need to be developed. An acceleration in development and a down-select of thermal shock synthesis should be used quickly. The evaluation of the thermodynamics of active site formation should have been previously considered.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The project team has demonstrated a positive interaction between partners and has used ElectroCat resources to a satisfactory extent to this point.
- The project has balanced collaboration between academia (national laboratory and university) and industry.
- There was a strong collaboration with Ballard Power Systems, Inc.
- The team has established collaborations between different organizations.
- The initial collaboration has been focused on the thermal shock method. More explanation of why this approach is necessary and how it is scalable would be useful because it is not clear. The other collaborators should be able to contribute significantly to the project in the future and have complementary expertise.
- Good collaboration with ElectroCat is demonstrated and should be expanded. The roles of collaborators were not clearly enunciated during the presentation.
- The team has a good composition of national laboratories, industry, and universities. It would be helpful if contributions from each member could be identified through individual slides.
- Although rather unclear, collaboration seems to be ongoing.

Question 4: Relevance/potential impact

This project was rated **3.1** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The idea of incorporating a dual-site catalyst to improve durability by limiting radical-induced carbon corrosion is critical for any advancement of carbon-based, non-PGM catalysts. This project is very relevant to the goal of shifting away from PGM cathodes. For non-PGMs, durability is as important as activity; this is often overlooked. If successful, this will have a significant impact on the shift to non-PGMs.
- Catalyst performance and catalyst scale-up synthesis for MEA engineering and testing (50 cm^2) are realistic targets. MEA engineering for performance improvement in both hydrogen–oxygen and hydrogen–air is going to be the focus for the next year.
- PGM-free catalysts with improved activity and durability will lead to fundamental changes in the fuel cell industry.
- This project may have an important effect on reducing ambient peroxide generation in PGM-free catalysts, thereby improving durability. It is not clear how important a peroxide scavenger is in the catalyst layer as opposed to the membrane (where scavengers are typically incorporated), but this question can be addressed by this project.
- The project is relevant and has the potential to address degradation in PGM-free catalysts. To have higher confidence in the positive impact of the approach, the team needs to show the current versus time at a constant voltage in an MEA, with and without the peroxide decomposer.
- Peroxide scavenging is likely to be an important aspect of PGM-free deployment. However, the relevance of rapid thermal shock synthesis is less clear, as is scalability. It is unclear how this will be scaled, whether by lasers or a superhot fluidized zone or some other method. Arc heating thermal gradients are extreme, and the application to the carbon material used here seems extremely difficult.
- Non-PGM catalysts are a long-term and high-risk technology. It is too early to evaluate the relevance of a specific application, such as an automotive fuel cell. Non-PGM catalysts have the potential to be enablers for future products.
- The performance in MEAs was not demonstrated. A dramatic delay in approaching the first go/no-go decision could result in the inability to carry out this technology.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- The general directions of the improvement area are acceptable.
- The proposed future work is well defined.
- The proposed future work addresses all of the potential issues, as well as what is required to successfully complete the project, but the team remains fairly vague on the work. At this point, the major hurdles include the low activity of the material and the molecular-level mixing of the two types of active sites. It is unclear how these will be addressed.
- The proposed collaboration with ElectroCat to demonstrate a material difference in durability using the consortium's newly developed active site degradation diagnostics could yield significant results. The team needs to report on a current-versus-time-at-constant-voltage test in an MEA, with and without the peroxide decomposer.
- While the future work listed is appropriate, there is insufficient detail to demonstrate how the current shortcomings will be overcome, especially with regard to the key thrust of thermal shock synthesis.
- The future work seemed broad and vague, without specific approaches enunciated. The most specific proposed future topic is the molecular-level integration of dual active sites. It is not clear how the project will accomplish this and whether it will have an impact on performance. It is uncertain whether peroxide is so tightly bound that an integrated catalyst will have more access to it than the current design. It is unclear how this can be demonstrated. A computational component is recommended.
- The proposed future plan was not correlated to the fact that the project team is critically behind on the performance targets established for the first go/no-go evaluation.
- Thermal shock activation should be hypothesized and verified in future work.

Project strengths:

- This is an important project to study the incorporation of peroxide scavenging in the electrode, as opposed to the membrane, and the team has made good progress in this regard by combining state-of-the-art electrocatalysts with effective scavengers. The project has a strong opportunity to improve on initial performance and demonstrate in an MEA with a comparison to scavengers integrated in a membrane.
- The project has decent ongoing collaborations and a world-class industrial leader in electrode and PGM-free development. A partial replication of PGM-free catalyst and peroxide scavenger development was achieved.
- The strength of this project is the project team's idea of incorporating dual active sites for the improved durability of the carbon matrix that makes up the catalyst. The preliminary evidence is encouraging.
- The team is pursuing a logical approach with the potential to improve PGM-free catalyst durability. The team has complementary capabilities.
- The project team is trying to explore some interesting ideas that are not currently being pursued by other groups.
- This is a strong team with a well-defined focus. This is a first-year review.
- This project's strengths include the materials synthesis and characterization.

Project weaknesses:

- There appears to be no clear plan to quantitatively understand the mechanism of scavenging and transport or the lifetime of peroxide throughout the MEA. Therefore, there are limited means with which to justify the integration effort and distinguish this approach from membrane-localized scavengers.
- This project is reinventing the wheel on catalyst and peroxide scavenger development and has not demonstrated good progress on either of these. Furthermore, the key original synthesis route is lagging and has been unsuccessful so far; the weaknesses and remediation of issues were not offered.
- The use of thermal shock needs to be removed and the funds reallocated appropriately. The key weakness of this project is the team's uncertainty in how to achieve molecular-level integration of the two types of active sites.

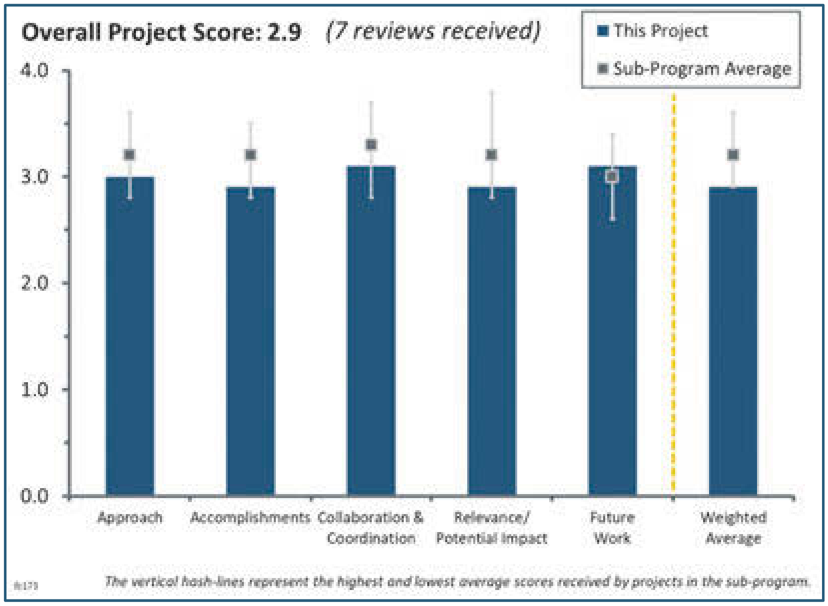
- There is a lack of chemical knowledge of thermal chemistry and the formation of active sites (for example, the role of zinc in synthesis). There is poor flexibility on the part of the principal investigator (PI) on making interim decisions and adjusting project objectives.
- More convincing evidence is necessary from an MEA test proving that the approach will improve durability.
- The catalyst performance is significantly behind other reports at the Hydrogen and Fuel Cells Program Annual Merit Review.
- Significant improvement in the MEA is a must for this project.

Recommendations for additions/deletions to project scope:

- It is recommended that the project team focus down to one thrust area, either thermal shock or peroxide scavenging, and evaluate meaningful metrics and milestones. If peroxide scavenging is chosen, the current approach is replicating well-established catalyst synthesis instead of developing something new. Similarly, for peroxide scavengers, it is unclear why the team does not use existing, more advanced approaches or even develop a completely new approach. If thermal shock is chosen, the team should evaluate the thermodynamics of approach and site stability quickly, and then evaluate the energy levels, controllability, and scalability of the different approaches—and create a quick go/no-go point. For example, it is unclear whether microwave synthesis can really achieve “shock” heating.
- A modeling component is recommended to follow kinetic mechanisms of ORR and degradation and to model peroxide concentration throughout the MEA. Also, an MEA diagnostic effort would effectively validate the model and justify design approaches. Unless the thermal shock approach can demonstrate clear near-term promise, dropping it from the project is recommended.
- It is recommended that the project establish a better understanding of N-hydrocarbon transformation and Zn removal from MOF during thermal shock activation. The PI should evaluate whether the team’s technique is more suitable to a precursor other than the MOF, perhaps for other nitrogen-containing organics.
- The project team should show that the thermal shock method is needed and scalable, or consider modifying that task. The team should also add a long-term MEA test showing improved durability at a constant voltage over time.
- It is recommended that the team remove thermal shock as a synthesis protocol and develop a defined procedure to address molecular-level mixing of the two active sites.
- Thermal shock activation should be well defined and hypothesized.

Project #FC-173: ElectroCat: Platinum-Group-Metal-Free Engineered Framework Nanostructure Catalysts

Prabhu Ganesan; Greenway Energy, LLC



Brief Summary of Project:

The project objective is to develop durable, highly active electrocatalysts for the oxygen reduction reaction (ORR) through a unique, bottom-up, rational design to enable a better understanding of the platinum-group-metal-free (PGM-free) active sites and improve activity. Fiscal year 2018 objectives include (1) developing high-throughput catalyst targeting porphyrinic and "phen"-type active sites, (2) exploring heteroatom doping, (3) beginning in-house membrane electrode assembly (MEA) optimization and fuel cell testing, and (4) positioning of the core laboratory ORR active site modeling with the experimental approach.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project's approach entails rational synthesis to incorporate known functionalities of catalysts into high-surface-area microporous frameworks by tailoring pore size to optimize the catalyst–ionomer interface.
- The approach is promising; the team's non-PGM cathode electrode demonstrated approximately 3–4 times less power density than current state-of-the-art (SOA) Pt/C cathodes.
- The use of porous N-containing organic frameworks provides a high-surface-area starting point for the synthesis that retains a large portion of the porosity and results in high-surface-area samples. Metal–organic-framework-based (MOF-based) materials have been shown to be effective precursors for active PGM-free catalysts. The team's approach to try to control the number of N coordinating the metal (Fe) atom is noteworthy. The approach for the modeling efforts is useful. The work suggests a "bottom-up" synthesis approach, incorporating known functionalities into microporous frameworks to develop PGM-free catalysts; however, the approach is still relying on pyrolysis to obtain active materials. It is unclear what the structure of the pyrolyzed materials is and what remains of the "known functionalities." It is not clear how the covalent triazine framework built from 4,4' dicyanobiphenyl (DCBP) can result in a "phen"-type chelating framework. The geometry of the framework has too large of a spacing between the N atoms for one Fe atom to be chelated by bonding to two nitrogens in the framework. Bonding to only one nitrogen in the framework is not likely to result in a stable Fe species. The strategy appears to place an emphasis on controlling the number of N sites bound to the metal center (first backup slide correlating FeN_2 to activity), but the characterization and analysis of the pyrolyzed product so far has focused on identifying the type of N in the product and, to date, has not looked at determining the number of N coordinated to the metal center in the pyrolyzed catalyst. More characterization tied to determining the geometry at the metal center is necessary.
- The principal investigator (PI) will examine PGM-free catalysts based on porphyrinic polymers and "phen"-type chelating polymers. There are numerous approaches to create/optimize the properties of

catalysts, including reducing particle size, increasing the nitrogen content, and metallization. It is not entirely clear how the PI will prioritize these tasks.
- Using porous organic polymers as ORR catalyst precursors has its own advantages over other systems, as demonstrated in the literature. The approach emphasizes its "inherent chemical and thermal stability." However, it is not clear where the stability advantage is since the same thermal activation is needed to convert the polymer to carbon.
- In terms of synthesizing and testing materials, the approach is good. The team is looking at a range of different precursor materials to achieve the highest possible activity. What is lacking is some definition and guidance to the approach. It looks like the project team is just feeling around in the dark, trying several different precursors and seeing what sticks. One of the major limitations of the specific focus on the precursor materials is the assumption that the final structure, N content, and degree of transition metal chelation can be controlled. The catalyst is synthesized by essentially burring in the precursors; it will never be possible to have direct specific control of that process. With that being said, insight could be gained through correlations, but that is better suited for a Basic Energy Sciences project than an Office of Energy Efficiency and Renewable Energy project. The project involves some computational analysis of the adsorption free energy of reaction intermediates on Fe-centered materials, but the connection to the experimental work is missing. It is hard to see how this is influencing the synthesis part of the project.
- The approach is aligned with the Electrocatalysis Consortium (ElectroCat) mission to improve PGM-free performance. It is not convincing that the technical approaches will be sufficient to address the durability of these materials.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project starts with a number of good polymer precursors with promising initial surface properties. Using a low-cost synthesis approach to porphyrin is helpful in reducing the PGM-free catalyst cost. However, catalyst performance needs to be improved, particularly for the "phen"-type system.
- The project began recently, on September 1, 2017, so the accomplishments have been modest. To date, the project team has completed Tasks 1.1, 1.2, 1.3, 1.8a, 1.8b, and 2.1. The synthesis of catalysts is progressing with some encouraging preliminary results—for example, the initial air performance of porphyrin-containing frameworks (as per slide 15), where the initial air performance is ~53 mA/cm^2 at 800 mV. There have also been some accomplishments regarding active site modeling, but it is unclear at the present time whether the model results will direct future experiments.
- The project team has shown some good results for a range of the precursor systems tested. Demonstrating the impact of Mn on the catalyst activity is promising. However, results from the computational work do not seem to be much different from previous results reported in the literature. Again, it is hard to see where the computational part fits in, as there is no apparent direct feedback to the synthesis.
- The project has obtained reasonable performance in an MEA in air for the brief period of time the project has been active. The project started less than a year ago. Characterization of the resulting materials is incomplete, and activity has not yet matched the current SOA for PGM-free materials.
- The project goals are not defined at full power, only at part power. The project's full-power performance is approximately four times less power than that of current SOA Pt/C cathodes; it is not clear where the goal needs to be. For example, if overall stack cost is 40% Cath PGM and 60% balance of parts, then SOA stack costs are \$40 + \$60 = \$100. Supposing this project reduces cathode catalyst cost 10 times, the trade-off shows only half the power density. The new PGM-free cathode stack costs would be projected to be \$4 + \$120 = \$124. Thus, in this example, the total cost of the stack would have increased.
- The team's approach should lead to higher active site density, which should improve catalyst mass activity. While the team still has until September to achieve MEA performance of >20 mA/cm^2 at 0.9 V, the current status seems significantly short of that. The other Year 1 milestones were not measurably challenging to achieve.
- The project team should optimize the synthesis protocol to prepare >400 mg of high-N-containing carbon-based materials per batch. More work is necessary to down-select polymeric materials for high-throughput synthesis.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The project team has developed good collaborations with good capabilities to evaluate the materials.
- There is good collaboration with partner institutions and an effective use of ElectroCat capabilities.
- This project has strong collaboration between industry and national laboratories.
- The project is a collaborative effort between Greenway Energy, Savannah River National Laboratory (SRNL), Northwestern University (NU), and Ballard Power System. No result/evidence was seen in the Hydrogen and Fuel Cells Program Annual Merit Review (AMR) presentation slides that the collaborators have made meaningful contributions. Collaboration tasks are listed in the AMR presentation. The project began less than nine months ago, so it may be too early to show results from team members other than Greenway Energy.
- There appears to be good collaboration between the modeling activities in this project and those at the Los Alamos National Laboratory. Collaboration between Greenway Energy and SRNL is going well. It is not clear what catalyst synthesis activities are being done at Greenway Energy and which are being done at other institutions (such as NU). It is not clear if Ballard has been involved yet.
- Greenway Energy and SRNL are in the same building, so the only funded external collaboration is with NU, whose polymer approach is complementary. Collaboration with other modeling and electrode optimization experts through ElectroCat may be useful.
- The presentation needs to identify individual member contributions clearly on the slides. It appears that the NU team has made a number of important MOFs and polymers, but this is not clearly identified in the presentation.

Question 4: Relevance/potential impact

This project was rated **2.9** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is a well-defined project. The synthesis of engineered frameworks should shift focus to the incorporation of Fe^{III} and Fe^{IV} sites. Experiments were designed based on predictions from density functional theory (DFT) models.
- The project is relevant, as PGM-free catalysts have a large potential impact on cost if performance comparable to Pt catalysts can be obtained.
- Using a porous polymer as a precursor represents an important route to PGM-free catalyst development.
- The exploration of new, inexpensive precursor materials is critical for further progress on these non-PGM materials. This project will be an important addition to the development of this class of catalytic material. While testing a range of precursor materials is necessary, a more fundamentally centered funding source is a better fit. This project must follow aggressive go/no-go decisions and down-selections to be competitive and relevant.
- Improving the active site density of the catalysts is an important effort. The project will not have much impact if the team cannot address durability as well. Fresh ideas for durability may be needed.
- The project meshes nicely with the ElectroCat program. There is a long-term need to reduce or eliminate the Pt content of fuel cell cathode ORR catalysts.
- It is not clear where the PGM-free full power targets need to be for automotive applications.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work is logical. The project is just getting to the point where results are coming in and strategies can be evaluated to see if adjustments need to be made to the original hypothesis.
- The proposed tasks are generally acceptable.

- The team's proposed future work is properly aligned to address the current limitations. One missing aspect from the future work is the assessment of material stability, in addition to activity. Both should be tested in parallel.
- The project team should optimize MEA fabrication to decrease high-frequency resistance and increase catalyst utilization; this is very important.
- The near-term future work should include some durability measurements on fuel cells.
- The direction of future work was unclear. There are several questions: how the experimental work will be prioritized, what perceived weaknesses in the catalyst will be addressed first, what will be optimized in the "phen"-type and porphyrinic-type catalysts, how many catalysts will be down-selected, whether rotating disk electrode data or fuel cell tests will be used to down-select, and how NU will contribute over the next year.
- The team needs to achieve activity targets and durability targets simultaneously. It is not clear that the approaches proposed will address durability. Improved active site density seems plausible with the proposed approach, but it still needs more work.

Project strengths:

- The project addresses an important subject—the development of highly active PGM-free ORR fuel cell catalyst powders. The project team is well qualified to carry out the proposed tasks. The PI has already collected preliminary data showing promising results.
- PGM-free cathodes have made a lot of progress over the past five years and offer the potential to address one of the biggest challenges for polymer electrolyte membrane fuel cells: PGM costs.
- The project's strengths include the identification of inexpensive precursor materials for the synthesis of active non-PGM catalysts. Another strength is the identification of the impact of mixed-metal centers.
- The team has an approach for increasing active site density, which should theoretically yield a much higher mass activity.
- The project has leading polymer synthesis experts helping to develop a PGM-free catalyst.
- One of the project's strengths is the attempt to control the M-N coordination number.
- This is a strong team and a well-defined project.

Project weaknesses:

- This project appears to be centered on a random survey of different precursor materials with tenuous guiding principles at best. It seems like the team is just gathering a few groups with experience and a few different precursor materials and trying things out. The approach needs to be more focused. The DFT analysis seems disconnected from the synthesis.
- Porphyrinic compounds have been examined in the past (e.g., by Yeager at Case Western Reserve University); that work ultimately failed. The stability of such compounds is still of concern. The team needs to focus on the ordering/prioritization of tasks to optimize the catalyst structure/composition/ properties in future experiments.
- This is a first-year review, and more work should be done to optimize the catalyst to be successful by the end of the project.
- Mass activity is poorer than would be expected if there were more active sites. The approach may not address durability.
- Appropriate full-power targets should be stated and justified, and some durability data should be shown.
- The catalyst performance needs to be improved through better collaboration between the team members.
- Dicyanobiphenyl bipyridine (DCBP) geometry does not allow the chelation of metal by more than one N in the framework.

Recommendations for additions/deletions to project scope:

- It is recommended that the team provide more information about the range of conditions to be examined to optimize catalytic activity. The connection between the modeling results and experimental work needs to be strengthened. There needs to be more collaboration with national laboratories, Ballard, and NU.

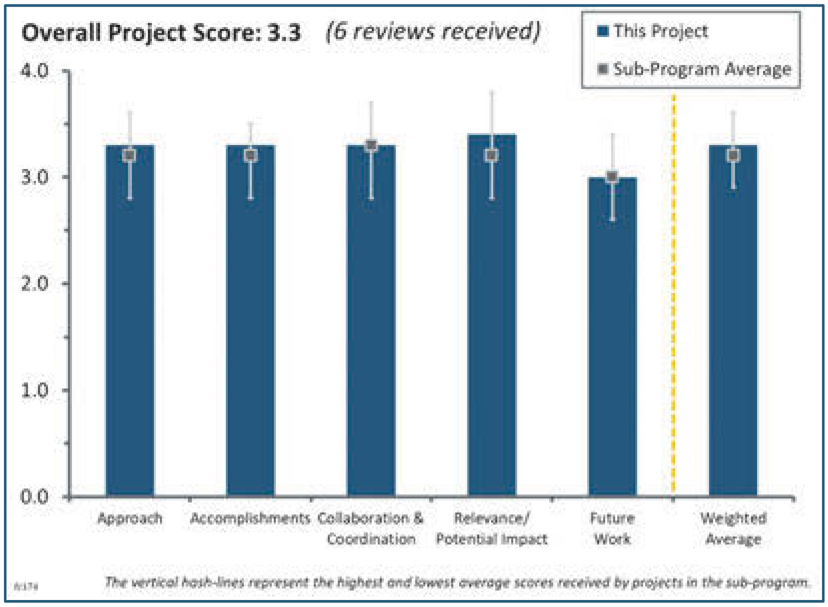
- Starting with DCBP and dicyanobipyridine (DCBPy), it is recommended that the team add additional nitrogen sources (small molecules) to adjust the M-N coordination number with these starting materials.
- Durability data should be demonstrated prior to optimization tasks.
- Durability and activity should be evaluated concurrently.
- Stability analysis needs to be added to the project.

Project #FC-174: Highly Efficient and Durable Cathode Catalyst with Ultralow Platinum Loading through Synergetic Platinum/Platinum-Group-Metal-Free Catalytic Interaction

Di-Jia Liu; Argonne National Laboratory

Brief Summary of Project:

The project objective is to develop ultralow-platinum@platinum-group-metal-free (PGM-free) nanofiber cathode catalysts that achieve all U.S. Department of Energy (DOE) fuel cell catalyst/membrane electrode assembly (MEA) performance metrics, particularly in the high current/power density region. The approach reduces platinum usage through synergistic interaction between ultralow-platinum and PGM-free sites by improving catalyst activity and durability/transport by using a porous nanofibrous network catalyst support instead of a conventional carbon support.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This low-platinum approach of low-platinum@PGM-free catalysts shows critical high activity in terms of rotating disk electrode (RDE) performance for an oxygen reduction reaction with PtCo on a calcinated Co metal–organic framework (MOF). Therefore, one of the 2025 technical targets (0.44 A/mg@0.9 V) on MEA performance has been easily passed. The project effectively shows the feasibility of low platinum loading at roughly 0.035 mg/cm^2 on the cathode, while the comparable performance to 2025 targets is still matched. The potential here lies in the better MEA performance with lower PGM loading than the DOE target of 0.125 mg/cm^2.
- The proposed approach is focused on the DOE Hydrogen and Fuel Cells Program (the Program) targets for reducing catalyst cost and improving durability and performance at high current densities. The technical approach is novel, well-thought-out, and feasible.
- Overall, this is a good approach, but it would benefit from the characterization of not just catalysts but also the carbon support/co-catalyst morphology and composition.
- The approach addresses all of the technical barriers and is technically sound.
- The approach calls for PGM loading to be very low on the cathode (<0.05 mg/cm^2), but higher loading with excellent power density may be an opportunity for lower grams of PGM per kilowatt and, therefore, an even lower-cost stack. A wider range of loading should be explored. If executed well, attempting to see whether active sites introduced by PGM-free materials could help to mitigate localized mass-transport losses at platinum particles would be a worthwhile approach. There is a high-current-density target in the project (1 W/cm^2) at the end. It may be preferred to have intermediate power density targets during the duration of the project. Electrospinning appears to offer the possibility of a catalyst preparation method that would be amenable to high-volume production, but the approach still leaves this unclear.
- The approach is a combination of electrospinning, PGM-free/stabilizing supports, and PGM-free catalysts. This is a promising approach, but the synergism claimed is not evident—and the possibility of platinum alloying with the residual base metals in the PGM-free support may be responsible for the observed

performance. Furthermore, the control case PtCo presented as a basis for claimed synergism is very poor, worse than pure platinum. Clarification on the actual approach materials and performance is necessary to keep the approach validity.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Outstanding progress has been demonstrated toward the goals of the overall project and DOE. Targets on Pt mass activity and loss in performance at 0.8 A/cm^2 and 1.5 A/cm^2 are exceeded, while targets on MEA performance at 800 mV and 675 mV in air are closely approached. One of the biggest accomplishments of this project is the development of a complex catalyst structure that incorporates (1) a durable PtCo catalyst with a core–shell structure and (2) a catalytically active support that promotes the activity of the catalyst, enhances durability of the catalyst–support structure, and provides good transport conditions at high current densities.
- The project is on track, with strong work being done on catalysts and electrochemical characterization combined with modeling.
- The project team appears to have met initial targets based on the data presented. There needs to be some certainty reported about exactly what synergistic catalysis is taking place.
- Pt/C (BASF) baseline data is low for mass activity. The baseline mass activity should be near 100 A/g$_{PGM}$ (fuel cell testing). No indication was given of the different properties of PF-1, PF-2, PNNF-8, and PNNF-9. Since material differences appear to have substantial impact on mass activity, high-current-density performance, and the response to the electrocatalyst accelerated stress test (especially between PF-1 and PF-2), it would be interesting to understand how the different materials generate the differences in results. However, this is not shown. With 1.25 A/cm^2 at 0.6 V, a low grams-per-kilowatt result might be calculated, but without the anode loading, this remains unknown. Good durability in the electrocatalyst cycle is shown for LP@PF-1, but since there is little to describe the specifics of PF-1, it remains unknown why this durability was achieved. The presentation leaves uncertain whether all samples in the LP@PF series are PtCo. It appears that there is in situ alloying of Pt with Co in PF-2, but PF-1 is also of interest, given its durability. To be convinced of synergistic mechanism between PF-2 and PtCo, the presentation would have to indicate Pt loadings and PGM-free catalyst site densities or loading. There are a number of questions that could be asked regarding how active sites get preserved during electrocatalyst cycling. Whether the Co-N sites are preserved is worth studying. Mass activity could still be maintained (and peroxide could still be low) even after PGM-free sites are lost. The model needs validation with some simple glass cell experiments. It is unclear whether peroxide generation actually decreases with the presence of PtCo and PGM-free sites, more than it would with just the sum of these. This question still needs to be answered since the fuel cell data (without loadings or some normalized parameters) does not yet say this. Since the LP@PF-1 material was difficult to condition, there needs to be some understanding as to whether a highly durable material can be made that is also easy to condition.
- MEA performances at 800/675 mV and <40% durability loss on one of the best catalyst systems are still off from the goals. The weakness is related to the ultralow Pt loading on the PGM-free support (~3%). Such ultralow loading makes the oxygen transportation to the PtCo surface very difficult. The low backpressure (50 kPa) might also indicate the flooding issue on the relatively thick catalyst layer of the MEA. The increase of metal loading on the calcinated MOF might be critical to meeting all DOE goals. The density functional theory calculation indicates the formation and migration of H_2O_2 intermediate, which contradicts the observed 4e- process from the RDE. It is unclear whether the migration rate and the direction of H_2O_2 were taken into consideration. This is another weakness and is subject to improvement. Another question is whether this approach can be scaled up to the 50 cm^2 MEA level.
- The milestones selected are not very relevant to the work described—materials are made and characterized, rather than specific performance targets met. As such, the milestones should be adjusted to be in line with the Fuel Cell Consortium for Performance and Durability (FC-PAD) targets and guidelines. The tests conducted are not in line with the correct protocols for support durability. The benchmark consists of poor performance materials that are not even close to the state of the art (SOA), and no comparison is made to the materials known to be closest to meeting fuel cell performance goals.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- This project is a well-coordinated effort between Argonne National Laboratory, Purdue University, and Northern Illinois University.
- This project leverages multiple partners that contribute significantly.
- This project's excellent collaboration is exemplified by Purdue University's contribution of modeling studies.
- An industry partner is suggested to test performance independently if the catalyst is further optimized.
- This is a small project so collaboration is harder. That said, the attribution to collaborators is unclear.
- It is almost impossible from the presentation to see what Northern Illinois is accomplishing. Purdue University is essentially working on a model that tells the project what it wants to hear. However, the model needs to be validated versus an electrochemical experiment. The project presents polarization curves that show LP@PF-2 performing much better than PF-2 or a PtCo/C catalyst. However, the Pt loadings are not shown, and the amount of PF-2 used is also not shown. Perhaps a combination of the PGM-containing and PGM-free materials were highly loaded to achieve the result, or perhaps the synergistic effect is true. However, it is difficult to see. Something from the Purdue University model should at least be directionally compared to something from fuel cell testing. The modeling collaboration could be much better integrated. The project is in sore need of a catalyst or catalyst-coated membrane supplier for collaboration. Otherwise, technology transfer is difficult.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project helps to address the cost and performance of polymer electrolyte membrane fuel cells. It exceeds initial performance metrics and, if successful, will help push toward reducing the cost associated with fuel cell manufacture.
- This is a transformational project that is very important for the success of the Program; it has the potential for a significant impact on technology development.
- This project is highly relevant in combining low-PGM and precious-metal-free catalysts and demonstrating the synergy between these two approaches.
- The project has met most of DOE's 2025 targets in terms of MEA activity and durability on LP@PF-1. The remaining milestones have been proposed for future work.
- A new oxygen reduction catalyst that targets high power density and durability with very low PGM usage is relevant to overcoming the barriers of cost and durability in the Fuel Cell R&D sub-program. Despite the relevance of the project to technical targets, there is some concern over batch size. While the project may be using techniques that appear amenable to high-volume production (heat activation of MOFs, use of electrospinning, etc.), no data are presented to confirm that high-volume production can be achieved. The project's collaborators are all universities and national laboratories, which makes it difficult to see how scale-up will occur or whether anyone would be interested.
- The relevance is difficult to judge because the project does not align with the established test protocols and benchmarks outlined in the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, and instead seems to be operating with little relevance to the SOA.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The future work proposed is solid, so long as it follows established relevant test protocols, reports relevant benchmarks, and ensures that results are validated externally. FC-PAD seems like a likely and relevant validator.
- Future work is based on careful analysis of past progress. Future work contains a concise plan with clearly defined milestones.
- The proposed future work aligns well with the current work and is a logical progression. Scaling up the work done at the cell level to a short stack would be interesting.
- MEA studies must be the priority for these catalysts, but an "improved understanding" of the catalytic mechanism is essential for the project to have value. A microkinetic approach is recommended to validate the conjecture that the consumption of surface peroxide explains the synergistic effect, and especially to validate this claim in the MEA context.
- The principal investigator (PI) proposes to meet the remaining project tasks and milestones. Besides that, it is suggested the team improve the Pt loading, improve the mechanical integrity of the MEA, and demonstrate the scale-up capability. A better understanding of the synergistic effect of two active sites is also necessary.
- The project has a short time left, but it would do well to provide more convincing data on the synergistic effect and to achieve high-current-density targets. Future work indicates some of the former but will focus on current density at 0.8 V. There is no discussion of conditioning time in the future work, although this may be an issue for the most durable catalyst. There is a drive to achieve the lowest Pt loading possible. However, it is the best combination of loading and power density that provides for the lowest Pt content in a stack. The project needs to maintain this perspective.

Project strengths:

- The project proposes a novel approach for the design of low-PGM-supported catalysts that addresses several important issues simultaneously: catalyst activity, support durability, and the mass-transport properties of catalyst layers. The team has strong modeling capabilities that were successfully used to identify the synergistic interaction between the catalyst and the support as an important factor affecting catalyst activity.
- The project's low-Pt design and SOA method have shown the potential of application. The approach addressed the key barriers with MEA testing slightly different from DOE target conditions. The team specifically achieved most DOE targets with quite low Pt loading at ~0.035 mg/cm^2 MEA. The MOF-based synthesis has the potential to improve the utilization of Pt in fuel cells. This project has strong technical expertise and avenues to achieve the remaining goals.
- The concept of using platinum with a PGM-free catalyst to mitigate local oxygen transport resistances is worth pursuing. The PI has a strong background with a particular class of PGM-free materials, namely MOFs. The power density and durability shown to date have been fairly impressive for some of the catalysts made.
- The project team has a specific set of targets and is hitting them well. There is good collaboration and a logical path forward.
- The project has strong catalyst and electrode characterization, as well as good collaboration on the modeling study.
- The underlying approach is promising.

Project weaknesses:

- An inappropriate reference was selected as a baseline for the comparison of results of fuel cell tests. The Pt/C MEA from BASF demonstrates SOA performance in neither a hydrogen–oxygen nor a hydrogen–air environment. Tail at high current densities is not usually observed at high current densities if SOA MEAs are tested under hydrogen–oxygen. PtCo-based SOA MEAs and catalysts need to be selected as a reference for comparison with the PtCo catalysts developed in the project, not Pt/C.

- The project team has not yet clearly demonstrated or modeled the synergistic effect that has been claimed. The project lacks collaboration with either a catalyst or catalyst-coated membrane supplier. The project also lacks fuel cell stack original equipment manufacturer guidance. This is evidenced by an insistence to achieve the lowest loading per area. The project team needs to further report on how material properties influence the resulting high current performance and durability.
- MEA performances at 800/675 mV and <40% durability loss on one of the best catalyst systems are still off from the goals. The weakness is the ultralow Pt loading of the catalysts, which allows the oxygen transportation issue to arise. The increase of metal loading on the catalyst might be critical to meeting all of the DOE goals. Another weakness is how to further explain the synergistic effect or prove its existence.
- Without relevant testing and comparison to the SOA, the true value is unclear. Furthermore, the overarching claim for synergism is unsupported.
- There seems to be some uncertainty in the synergistic reactions. A clear report on the reactions would be useful.

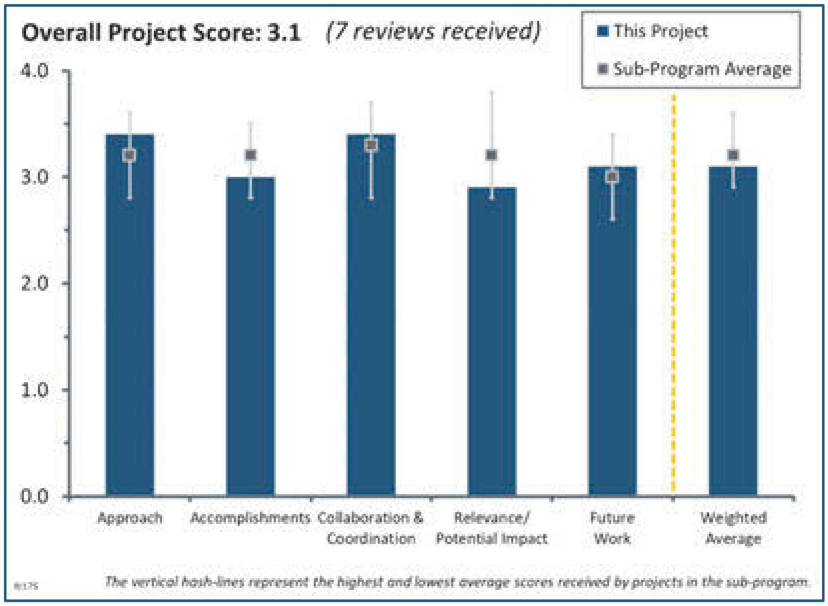
Recommendations for additions/deletions to project scope:

- No additions/deletions are recommended.
- The team should explore scaling up the work if the cell performance holds.
- Modeling needs to be shown to have a relationship with the experiments, or it should be removed from the project. The project should narrow its scope for the remaining time to show confirmation of the synergistic effect, achieve higher power density with a durable catalyst, and understand why catalyst durability exists. Some characterization should be done on active sites from PGM-free material after cycling. The conditioning time needs to be minimized.
- An MEA protocol is specifically needed for the MOF-based catalyst to maximize the performance, including durability.
- The project should be focused on relevant test protocols, appropriate benchmarks, and validation.

Project #FC-175: Polymer-Based Fuel Cells That Operate from 80°C–220°C

Yu Seung Kim; Los Alamos National Laboratory

Brief Summary of Project:



In high-temperature and low-relative-humidity fuel cell devices, one strategy to achieve cost savings is to eliminate or reduce the size of balance-of-plant (BOP) components, such as the humidifier and radiator. The objective of this project is to develop ion-pair coordinated polymers that can be used in fuel cells that operate at 80°C–220°C without humidification. The project is using density functional theory (DFT) modeling and small molecule study to determine the best candidate materials with strong ionic interactions. Membranes made of the selected materials will be manufactured, and the membranes' water tolerance and cell resistance in membrane electrode assemblies (MEAs) will be evaluated.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach of this project is great. It takes basic amines from the alkaline electrolyte membrane project and makes high-temperature proton conductors by reacting phosphate (H_2PO_4-) with quaternary amine and some added H_3PO_4 to get stable conductive and non-leachable membranes over a broad range of practical conditions.
- Starting with the DFT calculation before proceeding with the small molecule study was the right approach to determine the interaction between ammonium and phosphates. The MEA verification is the logical last step.
- The ongoing project phase with a limited duration of one and a half years investigates the feasibility of suitable ion-pair coordinated polymers regarding conductivity and water tolerance, and the team approaches this task well. However, with the key target and overall project goal of reducing the overall cost of the fuel cell system by using high-temperature polymer electrolyte membrane (HTPEM) fuel cell technology, special attention should be focused during the next possible project phases on:
    - Research on the feasibility of increasing power densities in hydrogen–air operation at reduced platinum loading to reduce overall cost.
    - The investigation of startup/shutdown procedures and the reduction of startup time. Startup/shutdown times have been one of the main reasons why HTPEM fuel cells have not been successful in automotive applications in the past
- Using an ion pair to enable the stability of a medium-temperature fuel cell system is a novel and creative approach. The concern is whether the polymer materials selected will be durable, as both have shown to be brittle at dry conditions. Also, over-potential losses due to phosphoric acid adsorption onto electrodes will likely always limit efficiency.
- The proposed approach appears very interesting and is based on new concepts of membranes.
- The first principle approach is good.

- This is an acceptable approach. There are barriers to these membranes that should perhaps be addressed, if within the scope. For example, swelling should be limited, and the team should address (or at least review) possible methods to reduce electrode poisoning from swelling.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- There has been great progress to date with the report of 0.8 W per cm^2 at 0.6 V at 200°C, and 200 W per cm^2 at 0.6 V at 120°C. The work also shows the possibility of running lower temperatures, such as 80°C, with the present membrane and claims of "proprietary membranes that have better performance and non-leaching ability." This is outstanding performance and durability for a fuel cell power source.
- Both the DFT calculation and small molecule study have been successfully accomplished and have achieved significant results. The MEA verification has been advanced significantly.
- Progress is good, based on the 18-month timeframe of the project and the focused scope.
- The project has met its go/no-go criteria.
- The results presented are encouraging. This new membrane leads to better performance than using HTPEM membranes but is far below state-of-the-art standard polymer electrolyte membrane fuel cells (PEMFCs), even with very high catalyst loadings. Durability is still unknown. Thus, much development is necessary to achieve DOE targets. In particular, the starting time and the performance below 80°C remain big challenges for the HTPEM fuel cells.
- There has been progress made in the identification of potential ion-pair coordinated polymers in the project. Initial testing results are looking promising, but significant additional work regarding durability testing, cold start, and catalyst loading reduction will be necessary in the next project phases to evaluate suitability for automotive applications.
- Encouraging power densities have been demonstrated, but pol curves were measured in oxygen (not air), with extremely high Pt loadings (approximately 10 times the PEMFC targets). Open circuit voltage (OCV) is ~800 mV, likely due to phosphoric acid adsorption, meaning drive cycle efficiencies are much too low. No plans were shown to address low OCV. The performance at lower temperatures is also quite poor, and there were no plans presented to address low-temperature performance, which would be a big problem during vehicle start-up.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- The collaboration with Los Alamos National Laboratory (LANL), Sandia National Laboratories (SNL), Rensselaer Polytechnic Institute (RPI), National Institute of Advanced Industrial Science and Technology (NIAIST Korea), University of Stuttgart, NanoSonic, Inc., and Toyota Motor North America, Inc. hits all the bases for developing a HTPEM fuel cell for automotive applications. The main work consists of making and testing the polymer fuel cell at SNL and LANL, with good modeling and testing support by others.
- This project includes much collaboration with U.S. laboratories and international research teams; the work appears to be well coordinated by LANL.
- This project has good collaboration; LANL is getting polymers from RPI, University of Stuttgart, and SNL. NIAIST Korea is doing DFT work.
- The project team was well identified to attain, integrate, and test different structures.
- This project includes a balance of members from academia and industry.
- The project is a close collaboration with other research institutions and some support from industry. Industry involvement should be strengthened in the project.
- A wide array of other research institutes (including those from abroad) has been in cooperation for this project. However, the exact contribution of industry partners is unclear.

Question 4: Relevance/potential impact

This project was rated **2.9** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project team has developed a high-powered (1 W per cm^2) HTPEM fuel cell. This may be DOE's "silver bullet" for making a practical fuel cell system with a minimum BOP. The BOP may be the most expensive part of the fuel cell, followed by the catalyst; using an HTPEM reduces the BOP, substantially offsetting catalyst cost plus raising the system efficiency on a well-to-wheel basis.
- The development of a high-temperature PEMFC membrane is of high relevance to achieving the DOE targets. If the performance and the durability achievements of the membrane are met, it will have a very high impact on the development of HTPEM fuel cells and on the transport applications.
- Addressing the fuel cell costs by improving fuel cell cost efficiency and performance by eliminating the BOP components, particularly the humidifier, is absolutely relevant and serves the goals of DOE.
- The current state of the art in automotive low-temperature fuel cells has improved significantly in the last few years. In some automotive fuel cell topologies, the humidifier has been removed; sufficient cooling, while still being an important development target, can be realized in common vehicle architectures. With this recent progress in low-temperature fuel cells, the benefits of high-temperature fuel cells should be reevaluated, and the team should carefully analyze whether cost targets (e.g., power-specific platinum loading, additional cost for high-temperature coolant loop) and performance targets regarding cold start capability and durability can be achieved. Strong industry support will be necessary to achieve a technology readiness level similar to low-temperature PEMFCs.
- The membrane alone cannot make the fuel cell into a high-temperature unit; catalysts and other materials are also necessary to work at such temperatures. Therefore, those particular perspectives are necessary to justify this project's focus.
- There are many, many barriers to this technology's working: membrane swelling, catalyst or catalyst ionomer-type poisoning, metal decay/agglomeration, electrode support corrosion, and low-temperature flooding. Phosphoric acid will slowly (and permanently) leave the MEA over thousands of hours. It is highly unlikely that the industry will address/solve these issues within the next 5–10 years.
- It is not clear that there is a push for higher-temperature fuel cells for automotive applications (as the project claims). The project's targets do not align with automotive requirements for power density, efficiency, cold start, or durability.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- After completion of the first project phase (the identification of feasible ion-pair coordinated polymers), the proposed technoeconomic analysis (TEA) should be performed as the next step to compare the potential of the high-temperature PEMFC with current state-of-the-art low-temperature PEMFC technology. With the higher operating temperature, alternative applications such as stationary combined heat and power might be considered, where the higher-temperature heat and the better contaminant compatibility (if coupled with a fuel processing system like a methane fuel processor) might provide additional benefit for high-temperature PEMFCs, compared to low-temperature PEMFCs, and might make the high-temperature fuel cells more attractive for these types of applications.
- This project ends soon, and the team has a good vision for more work. LANL and the members of the Toyota cooperative research and development agreement will work on electrode reactions. The team cites a need for electrode and membrane development and technology validation and scale-up. This project should be refunded and continued.
- The proposed work is in line with the short time remaining in the project.
- The proposed future work looks good.
- The only valuable future work is the hydrogen–air fuel cell testing and in situ water tolerance testing. Surprisingly, there did not seem to be any plan to down-select between the membrane and ionomer

concepts under evaluation. There is no planned future work focusing on improving OCV or low-temperature performance.

- Even though the ion-pair coordinated polymers have been shown to work fine as part of the project, a large number of substantial challenges remain (e.g., ionomer design and membrane development), each of which warrants its own project of large magnitude (i.e., these fuel cells seem far from commercialization).
- For fuel cell testing, other materials, such as catalyst and bipolar plate, should be identified.

Project strengths:

- The project's strengths include the systematic approach to reach the targets of the ongoing project phase. Progress has been achieved, considering the relatively short overall project duration. This project also has the involvement of several international research institutions.
- This project incorporates a creative approach of ion-pair interactions that seems to address the issue of acid loss in acid-base-interaction-based medium-temperature fuel cells.
- This project would have won the 2005 to 2009 "DOE HTPEM Competition" if it had been going on back then. The project has essentially overcome all of the barriers to a HTPEM fuel cell.
- The biggest strengths of the project are its high relevance, the remarkable progress that it has made, and the outstanding results that were achieved.
- A real strength of this project is its high level of domestic and international collaboration.
- This project has good work and focused goals.
- The strength of this project is material synthesis.

Project weaknesses:

- There is no particular weakness to underline, except the short duration of this kind of project (i.e., less than two years).
- With the further advancement of low-temperature PEMFC technology, some of the advantages of the high-temperature PEMFCs that motivated this project might have been reduced. This should be evaluated in a TEA as a next step.
- The project's weakness is its relevance to the industry. Success would greatly reduce BOP; however, multiple difficult and fundamental problems are in the way.
- The project does not address all of the critical requirements necessary for automotive applications, including efficiency and cold start. These may be critical flaws of this approach that are not addressed in this project.
- Many challenges still seem to remain for commercialization.
- This project needs more work.

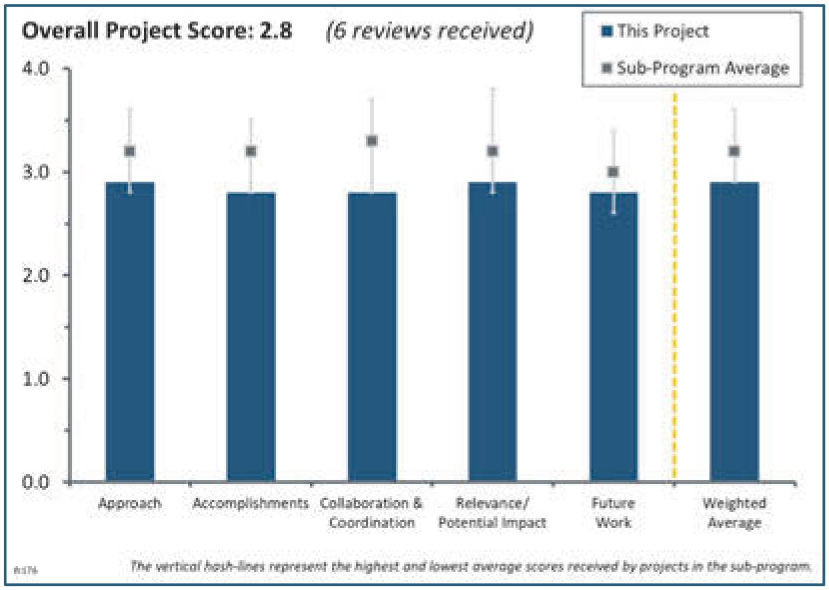
Recommendations for additions/deletions to project scope:

- As a next step, a TEA is recommended to compare the potential of high-temperature PEMFC technology with the current state-of-the-art low-temperature PEMFC development status. Platinum loading, durability, and start-up performance should be investigated.
- This project should prioritize addressing the low OCV in the fuel cell tests. The mechanisms should be understood and mitigation strategies developed. Otherwise, the efficiency will be well below automotive targets, and any other work on improving durability and reducing area-specific resistance would be moot.
- The project team should explain new "proprietary" membranes; that is, the team should address whether the membranes leach phosphoric acid when they perform at low temperatures—this is critical. A low-temperature startup or "cripple" mode would be excellent for a fuel cell power source. This project should be continued.
- The MEA and the total fuel cell material concept should be identified to justify this membrane development.
- It is recommended that the project team continue the investigation of the type of membranes.
- It is recommended that the team assess the metal dissolution rate at 160°C versus 120°C versus 80°C for the cathode.
- A deeper collaboration with industry partners seems desirable.

Project #FC-176: Fiscal Year 2017 Small Business Innovation Research (Phase II Release 1): Novel Hydrocarbon Ionomers for Durable Polymer Electrolyte Membranes

William Harrison; Nanosonic, Inc.

Brief Summary of Project:



Commercial polymer electrolyte membrane (PEM) technology is primarily based on expensive perfluorosulfonic acid ionomers. Hydrocarbon membranes represent a lower-cost alternative, but their utilization is currently limited because of their inferior performance and durability. This project is developing high-molecular-weight aromatic hydrocarbon membranes that possess polar moieties along the polymer backbone and pendant quaternary ammonium groups. This innovative chemistry will facilitate the fabrication of stable phosphoric-acid-doped ion-pair membranes for polymer electrolyte membrane fuel cells (PEMFCs) capable of 120°C operation for transportation applications.

Question 1: Approach to performing the work

This project was rated **2.9** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- A novel membrane chemistry was proposed. The membrane composition is based on hydrocarbons (providing lower cost) with a sulfur group (providing improved durability due to the scavenging properties for hydrogen peroxide and radicals) and polar moieties (giving high conductivity and lowering the leaching rate of phosphoric acid, improving durability).
- This Small Business Innovation Research (SBIR) project is reasonably effective so far. The preliminary results are very interesting and have the potential to make some important contributions to overcoming some barriers facing the development of high-performance fuel cells.
- The project is fabricating stable phosphoric-acid-doped membranes to enable transportation PEMFCs to operate at 120°C.
- The synthesis of novel phosphoric-acid-containing polymers has relevance for potentially improving the performance of phosphoric-acid-based fuel cells. The choice of ammonia-group-containing polymers due to interactions between phosphate and ammonium offers some potential for improvement, particularly at very low water content. The primary limitations of phosphoric acid fuel cells—phosphate ion absorption and tolerance to liquid water—do not seem to be addressed.
- The focus on hydrocarbon polymers and the platform is an interesting approach, although these materials have been examined in the past. The focus on higher-temperature performance is important. The focus on structure/function properties makes for an important and good approach. The team should describe the scale of the current manufacture/fabrication and address whether the project will move toward roll-to-roll-type assemblies. It is unclear why phosphoric acid is being used instead of something similar imbibed with sulfuric acid.
- For the stated transportation application, while high-temperature (up to 120°C) performance is strongly desired, performance at low temperature (-30°C to 80°C) is paramount, as vehicles must start and perform adequately (meeting customer expectations) from ambient temperature. There does not appear to be a

viable path for this material set to provide acceptable performance in these conditions (which will include liquid water at lower temperatures, at least near a cell outlet). There are also questions as to the stability and durability of these materials at normal automotive and startup conditions (phosphoric acid leaching under wet conditions).

Question 2: Accomplishments and progress

This project was rated **2.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This project has synthesized high-molecular-weight poly (thioether benzonitrile) copolymers with tailored compositions and tough films, with good thermo-oxidative stability. The team has demonstrated chloroacylation functionalization of copolymers and reaction conditions for reasonable reproducibility. The team has also fabricated quaternary ammonium-functionalized membranes and developed surface treatment for thin (<20 µm) and mechanically durable PEMs. The project team has demonstrated >150°C hydrated glass transition temperature of down-selected membranes, low dimensional changes (swelling), and good wet–dry cycling stability. Finally, the project has fabricated membrane electrode assemblies (MEAs) and showed stable conductivity over a wide range of temperatures and relative humidities (RHs).
- Membranes with a uniform thickness were synthesized and tested. For instance, membranes retain water at temperatures >120°C, are thermally stable up to 200°C, and have a glass transition temperature exceeding 150°C. Membrane mechanical properties were measured (tensile strength and elongation at break). The membranes resisted to a simplified dry–wet cycling version (25 cycles). Interestingly, the membranes were dimensionally stable in the in-plane direction, whereas a 50% change was noted in the through-plane direction. This anisotropy was not purposefully created, and it remains unexplained. The membrane conductivity is significantly better than Nafion under dry conditions in a temperature range of 80°C–200°C. Fuel cell tests have shown stable performance under dry conditions. However, performance is relatively low even with oxygen, rather than air, operation. From that standpoint, the fuel cell tests did not include specific measurements for the interfacial resistance between the membrane and catalyst layer ionomer. The proposed membrane chemistry is potentially amenable to solubilization to create catalyst inks, which would decrease the risk of a significant interfacial resistance. Several other key properties have not yet been measured, including oxygen and hydrogen permeability for both ionomer and membrane forms, and durability (i.e., resistance to hydrogen peroxide and radicals, dry–wet cycling over longer periods).
- Reasonable progress has been made in the synthesis of membranes and in evaluation of some membrane properties. However, more testing of the membranes under practical fuel cell operating conditions is necessary to confirm the claimed advantages of the proposed membranes—especially the long-term stability of the membrane. It is noted that Nanosonic, Inc. does not have the facilities for fuel cell testing; thus, closer collaborations with national laboratory partners are important to improving the rate of progress.
- The team has been successful in fabricating 20 µm membranes and has tested for conductivity, thermal stability, and mechanical strength. However, conductivity is far too low for transportation applications in which 0.1 S/cm or greater is required at operating temperatures between ~0°C and 80°C–100°C. If performance can be improved, the team will still need to demonstrate phosphoric acid stability.
- The work is fairly new and has shown new polymers and reasonable polymer performance. The group has shown improved performance in terms of membrane conductivity and has also shown reasonable phosphoric acid fuel cell performance. However, the results obtained to date do not suggest that these materials will replace current device materials.
- It is not clear whether the swelling and mechanical properties (e.g., pinhole formation and cracks in the membrane) are an issue or how they are being handled. Good progress is being made toward making the membrane thinner and less resistive. It is unclear whether the ionomer in the catalyst layer is being developed as well. The wet conditions in the MEA and whether there is liquid that is leaving the system for the imbibed system are both unaddressed, as are the peroxide testing and chemical accelerated stress tests. The team showed good results with the higher glass transition temperature (Tg) polymer chemistry, but it is unclear whether that limits the overall mechanical properties (brittleness) and the conductivity.

Question 3: Collaboration and coordination

This project was rated **2.8** for its collaboration and coordination with other institutions.

- For SBIR projects, collaborations tend to be more limited. The inclusion of Los Alamos National Laboratory (LANL) to do some of the fuel cell testing is an important accomplishment.
- The project team's collaboration seems good and appropriate.
- On a positive note, the team has engaged with LANL to develop MEAs for polarization curve testing. However, it is unclear whether analysis and learnings from these collaborations have been communicated. For example, the polarization curve (on slide 16) shows progressively reduced voltages at lower temperatures. High-frequency resistance (HFR) testing was presumably performed (if not, it should be) and would indicate if this reduction was solely due to lower conductivity at low temperatures or if it was limited due to flooding. This feedback is necessary for product improvement.
- Three partner organizations (U.S. Fuel Cell, Nissan North America, and LANL) were mentioned, but only one was clearly collaborating (LANL completed fuel cell tests).
- Some collaboration exists; however, coordination between partners could be significantly improved in the area of evaluation of high-temperature membranes in fuel cells under practical operating conditions. It is important to validate the claimed advantages of the proposed membranes in fuel cells under actual operating conditions.
- The fiscal year 2018 poster showed limited contribution from one partner and no contribution from other partners.

Question 4: Relevance/potential impact

This project was rated **2.9** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The commercial viability of fuel cell technology depends on (and is sensitive to) energy efficiency, durability, and cost. The operation of PEMFCs at higher temperatures could significantly increase energy efficiency and reduce the cost. Thus, if successful, the project has the potential to significantly advance progress toward the goals and objectives of the Hydrogen and Fuel Cells Program (the Program).
- The novel membrane has the potential to simultaneously reduce cost, improve durability, and have good ionic conductivity at high temperatures and low reactant stream relative humidities.
- The project is relevant to the Program's goals in that automotive stack operation at higher temperatures (up to 120°C) is desirable for extreme operating conditions (e.g., climbing a hill at a hot ambient temperature). However, more important is the performance (conductivity) at this high temperature, which requires 0.1 ohm/cm. Even more important is that this high conductivity is achievable over a broad range of temperatures and RHs, representative of real-world automotive fuel cell operation ranging from startup (-30°C–40°C), warmup (up to normal operating temperature, typically ~60°C), and normal operation (typically 60°C–90°C). This project appears to prioritize the high-temperature conditions without recognizing the imperative of the other, more typical, conditions.
- The project is relevant for moving toward higher-temperature performance, although there is still a question regarding whether the Fuel Cell Technologies Office and fuel cells should go in that direction. If successful, the project could have an impact, but issues related to polybenzimidazole (PBI) and the fact that it somewhat lacks commercialization are not seen as being overcome in this project.
- The measured membrane conductivity at 80°C is too low. Considering that the automotive fuel cells will spend the majority of lifetime at even lower temperatures, such as 60°C–70°C, this is a serious issue that must be addressed sooner rather than later. Perhaps the project should develop an accelerated test to demonstrate the long-term stability and retention of the phosphoric acid group under fuel cell operating conditions. The fuel cell performance with the fabricated MEA in hydrogen–oxygen is extremely poor. The performance will be even worse in hydrogen–air at reasonable stoichiometry and is unlikely to improve in humid environments. It is difficult to judge the cell performance without information on catalysts and Pt loadings.

- Phosphoric acid fuel cells have limited impact on many of the DOE's primary targets for performance and cost. Phosphoric acid systems have had limited impact commercially; this project tangentially addresses some of the performance issues that may have cost implications, but the work has nothing that makes a significant cost impact.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The proposed future work is completely reasonable and offers potential for continued incremental improvements.
- The stated plans are sensible; future work will support layer investigation and the establishment of structure–property relationships. For automotive application, future work on the following is vital: improved conductivity at low temperatures, evaluation of material durability, and stability at low-temperature and high-RH (including liquid water) operating conditions. If the material can pass these tests, the project team should also work on operation under the DOE durability stress test protocols.
- Future work is commensurate with the project. It would be good to see more comparison to baseline PBI systems as well as state-of-the-art (SOA) fuel cell MEAs and membranes, beyond just conductivity. More mechanical compression is recommended, including perhaps looking at composite structures. Some focus on the ionomer should also be added, and the team should look at more fundamental issues of acid leaching, as well as how to mitigate those issues.
- Future work includes the use of a novel functionalized monomer, which would allow for greater ion-exchange capacity control during the membrane synthesis. However, the addition of a textile structural support to reduce cost remains unclear. How this support will reduce cost is unknown. Reactant permeability through the ionomer (for catalyst inks and reducing the interfacial resistance with the membrane) and membrane durability should be given higher priority. A more controllable synthesis and a lower-cost membrane are not useful if the ionomer and membrane do not have the potential to meet targets.
- The project team needs to place concerted effort on improving conductivity at lower temperatures, demonstrating the stability of the phosphoric acid group, and determining the causes of poor cell performance. The team should consider collaboration with system analysis experts to understand the limitations of this high-temperature membrane in automotive fuel cells and determine areas requiring improvement and focus.
- The outlined future plans are logical and built largely on past progress. However, more critical evaluation of the membranes and MEAs in actual fuel cells under practical operating conditions (e.g., subject to large current flow at high temperatures) is necessary to overcome some barriers.

Project strengths:

- The development of advanced high-temperature membranes is critical to the development of high-performance fuel cells. The proposed PEM has the potential to make an important impact on the development of high-temperature fuel cells. Some preliminary results to date are interesting, but further validation in fuel cells is necessary.
- The project has a good team, with the right capability and approach toward making higher-temperature membranes. Progress on conductivity and select membrane properties is good.
- In a relatively short development period, the project was able to demonstrate a thin membrane with some conductivity, strength, and thermal stability.
- The proposed membrane chemistry is novel and has the potential to simultaneously address key barriers (such as cost, performance, and durability).
- The project has a good, novel approach to an incremental materials advancement for phosphoric acid fuel cells.
- The project team has expertise in developing ionomers and fabricating high-temperature membranes.

Project weaknesses:

- Several key membrane properties (reactant permeability for both ionomer and membrane forms, interfacial resistance between ionomer and membrane, and durability) are currently missing, and therefore, a complete assessment cannot be finalized. Additionally, these aspects should be given a higher priority in future work. The contributions of two partner organizations are currently unclear. A data management plan is currently missing.
- Confirmation of the claimed advantages of the proposed membranes has yet to be demonstrated in fuel cells under practical operating conditions, especially for long-term durability. Closer collaboration with the fuel cell testing partner is necessary.
- The project team does not address, or does not comprehend, the full range of requirements and imperatives for an automotive fuel cell membrane (though the project may have some possible applicability to stationary power).
- More focus is necessary on mechanical properties, as well as transport. The ionomer and MEA and how these overcome existing SOA material issues seem uncertain.
- There is insufficient conductivity at low temperatures, and the long-term stability of the phosphoric acid group was not demonstrated. The cell performance was also poor.
- This project team did not take on water tolerance or the phosphate anion adsorption losses that tend to be major weaknesses and concerns for phosphoric acid fuel cells.

Recommendations for additions/deletions to project scope:

- For automotive applications, addressing the following is recommended: conductivity at low temperatures (-30°C–60°C), as well as the demonstration of stability and durability at these temperatures and under fully humidified conditions (including the presence of liquid water), including retention of the phosphoric acid sites. Upon successfully meeting the above, it is recommended that the team test to the DOE durability stress protocols.
- A broader materials space investigating more cation groups and/or tethering strategy could provide more fundamental information on the role of these cations in phosphoric acid retention and membrane properties.
- It is necessary to conduct more testing of PEMs and MEAs in fuel cells under practical operating conditions for a longer period of time (e.g., large current density at high temperatures).
- External collaboration with a systems analysis group is recommended.
- It is recommended that the team add compression and blister testing to the project.

2018 – Technology Acceleration and Hydrogen Infrastructure R&D Summary of Annual Merit Review of the Technology Acceleration and Hydrogen Infrastructure R&D Sub-Program

Summary of Technology Acceleration and Hydrogen Infrastructure R&D Sub-Program and Reviewer Comments:

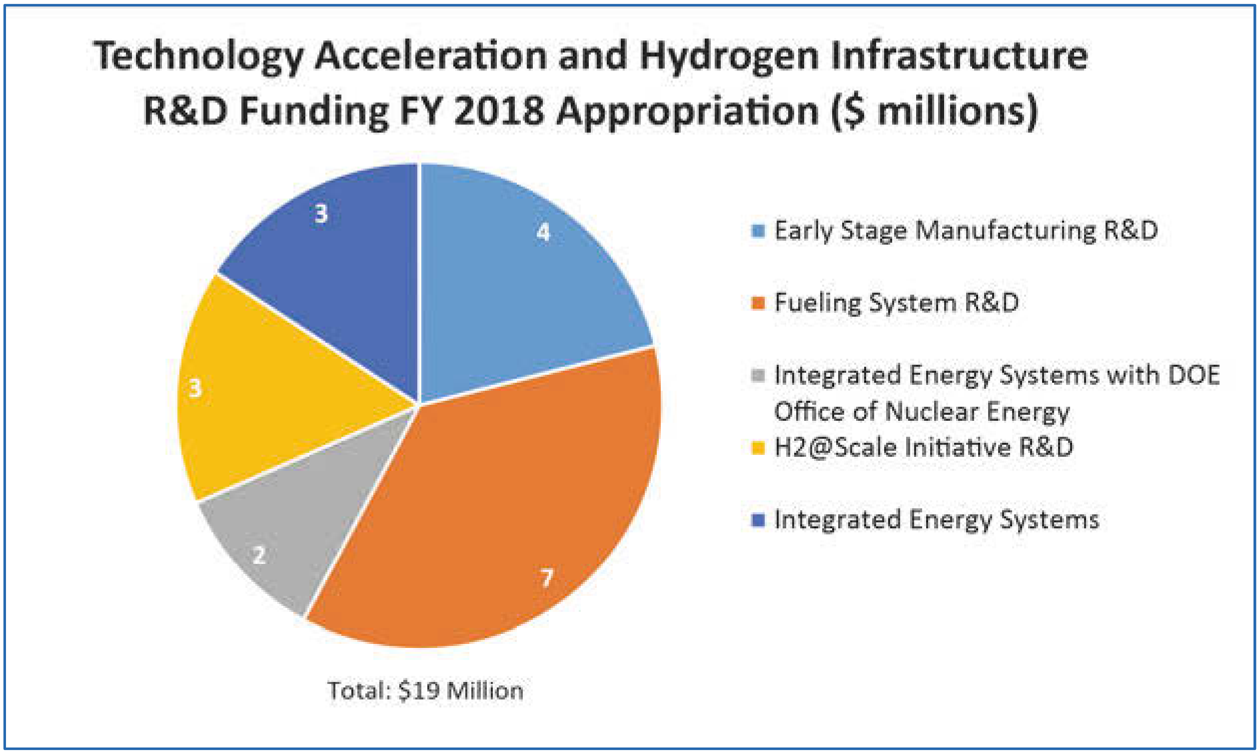
The Technology Acceleration and Hydrogen Infrastructure R&D sub-program aims to enable hydrogen technologies that support hydrogen infrastructure development and hydrogen production from diverse domestic resources such as solar, wind, and nuclear power through innovative research and development (R&D). The goal is development of reliable, low-cost, and safe hydrogen infrastructure technologies for multiple applications. The sub-program's portfolio of early-stage R&D activities support the H2@Scale concept, including R&D to identify and develop technologies that provide significant cost reductions in hydrogen storage, use, and transport. R&D focus areas in 2018 included (1) refueling station R&D (compression, storage, and dispensing), (2) hydrogen transport R&D (liquefaction, bulk hydrogen carriers, and storage), (3) materials compatibility R&D, and (4) integration with diverse generation sources and end-use applications (e.g., integration of hydrogen technologies with nuclear generation and the grid, advanced material and component fabrication technologies and processes, and system validation). The sub-program also collaborates with state and local organizations and other federal offices and agencies (such as the U.S. Department of Defense, National Science Foundation, U.S. Department of Transportation, and the DOE Offices of Science, Fossil Energy, and Nuclear Energy) to leverage outside activities, coordinate efforts, and build opportunities for new technology applications and deployment.

The Hydrogen and Fuel Cells Program (the Program) reviewers commended the Program's focus on H2@Scale and the prioritization of hydrogen production and infrastructure R&D to lower the cost of hydrogen production and increase hydrogen supply. They included the H2@Scale launch and grid integration activities among the Program's top accomplishments in 2018 and suggested that a consortium approach would be useful to encourage coordination and collaboration among the many stakeholders in grid integration. Reviewers recognized the importance of government funding for early-stage R&D for innovation and breakthrough science, but they emphasized the critical need for continued government support of applied R&D in the implementation and validation of new hydrogen and fuel cell technologies. Also recognized as a key Program strength was stakeholder collaboration, including the Program's work with international agencies and organizations, other federal and state agencies, the Hydrogen Council, and other industry stakeholders. Reviewers suggested an increased focus on medium- and heavy-duty vehicle fueling, high-volume manufacturing technologies, demonstration of H2@Scale in the field, and first-of-kind questions about how to successfully manage energy sector transitions. Reviewers also recommended continuing and broadening coordination with outside stakeholders important to H2@Scale, including the nuclear industry, fuel production and distribution industry, and state and regional utility regulators, as well as increasing participation of the manufacturing industry as suppliers to the fuel cell industry.

Project reviewers also were impressed with specific project highlights and accomplishments, as detailed in the project review reports that follow.

Technology Acceleration and Hydrogen Infrastructure R&D Funding:

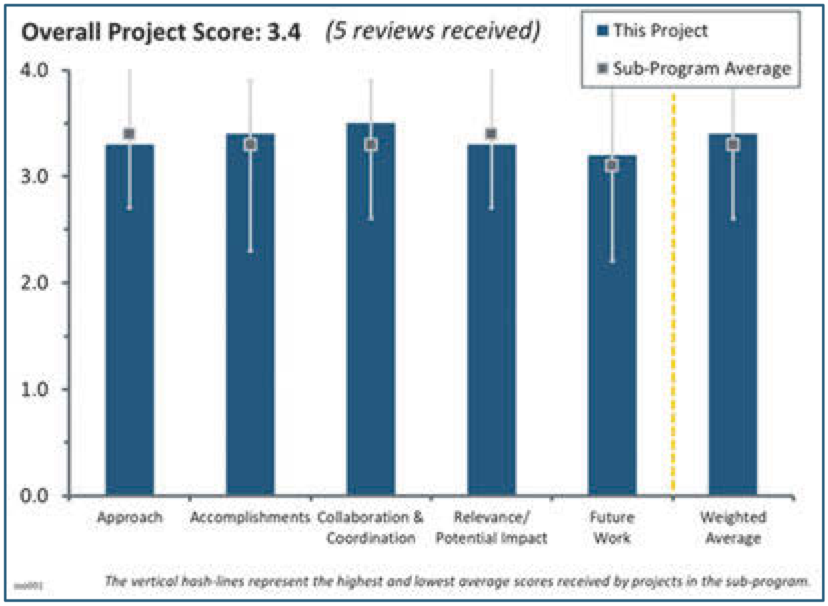
The fiscal year 2018 appropriation for the Technology Acceleration and Hydrogen Infrastructure R&D sub-program totaled $19 million. The funding was focused on early-stage manufacturing, integrated energy systems, H2@Scale concepts, fueling system R&D, and integrated systems with nuclear hybrid energy systems; this breakdown is depicted in the figure below. Future work in the sub-program is expected to focus on applied early-stage research and technology for the H2@Scale initiative related to hydrogen production and storage, hydrogen energy storage, materials compatibility, and innovative hydrogen carriers.


Technology Acceleration and Hydrogen Infrastructure R&D Funding FY 2018 Appropriation ($ millions)
4
7
2
3
3
Early Stage Manufacturing R&D
Fueling System R&D
Integrated Energy Systems with DOE Office of Nuclear Energy
H2@Scale Initiative R&D
Integrated Energy Systems
Total: $19 Million

Project #MN-001: Fuel Cell Membrane Electrode Assembly Manufacturing Research and Development

Michael Ulsh; National Renewable Energy Laboratory

Brief Summary of Project:



The objectives of this project are to (1) understand quality control (QC) needs from industry partners and forums, (2) develop diagnostics by using modeling to guide development and in situ testing to understand the effects of defects, (3) validate diagnostics in-line, and (4) transfer technology to industry partners.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The National Renewable Energy Laboratory's (NREL's) approach, focused on early-stage technique development coordinated with industry, is excellent. NREL's actual development of diagnostics and validation in-line on actual membrane electrode assemblies (MEAs) is far superior to merely doing an analysis.
- NREL is doing some fine work in this project. The collaborative approach to this project is exemplary, and the project team is working on technology that will be essential for ultimate large-scale manufacturing of polymer electrolyte membrane fuel cell (PEMFC) MEAs.
- This project is a continuation of an enduring effort to expand technology in fuel cell manufacturing. Certainly during the last years when this activity was underway, commercialization of fuel cell technology continued unabated. NREL has had the freedom to "pick their battles." Fuel cell technology has morphed into another engineering discipline. There is excellence written across the NREL activity. However, as is necessary, many of the activities have been accomplished under secrecy agreements, and while what is presented is finished work, it is clearly not all the finished work. Such an arrangement is essential. Even so, the "work" is not fully described, and thus judging on "performing the work" has to remain fuzzy.
- The approach to performing the work appears to be strong. This is validated by the partnership with Mainstream to commercialize vision-based scanning for defects.
- This project's approach is speculative on types of defects that could be significant. It artificially introduces the defects into a MEA/membrane manufacturing line, then manufactures the product to see whether those defects could be detected in the manufacturing line. The approach should be to scan commercially produced MEAs or membranes and look for manufacturing defects, study the impact of the discovered defects on fuel cell performance, study ways to quickly screen MEAs and/or membranes for those existing manufacturing defects, and work with the manufacturer to identify the cause of manufacturing defects that have an impact on performance.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The NREL team completed multiple demonstrations of in-line QC methodologies, all of which have potential for use in future manufacturing lines. As the scale of PEMFC manufacturing expands multifold over the next several years, these tools will be available for adoption. For example, the ability to find and localize pinholes in the membranes in an in-line (continuous) manner has enormous potential for reducing manufacturing cost and improving reliability.
- The project emphasizes the analysis of starting materials used in roll-to-roll (R2R) processing, processing like 3M uses to make Scotch Tape. During the duration of the NREL activity, very significant improvement in fuel cell performance happened. For instance, a 75-kW stack suddenly morphed into a 100-kW stack with no apparent change in weight or volume. The presentation covers some rather simple experiments, such as looking for pinholes in membrane materials. This is elementary. It is impossible to know how much NREL contributed to the success of the existing fuel cell industry, but it is apparent that the amount is *not* zero. As in many situations, it is impossible to fully understand individual contributions in a huge endeavor. General Motors (GM) claims they invested $2.2 billion in fuel cells to date, but there have been many people, with NREL in the middle of it. This is a good investment.
- The project presents numerous data examples of defect detection using a variety of approaches. Demonstration that defects can affect cycle performance yet have no impact on initial performance is a key finding. The project uses Lawrence Berkeley National Laboratory modeling to predict the impact of using a cooling jet for the through-plane reactive excitation approach, but actual test measurements would be more convincing.
- Many good defect scanning tools were developed. The defect impact in cell performance was studied. The DOE goals and barriers “E” and “H” identified on slide 2 should be done upon receiving MEAs at the stack assembly site.
- The team has reported progress on the various inspection methods investigated, including demonstration that the approach works. The project did not directly include what impact those methods have on the identification of defects. For instance, it was unclear how many defects were missed prior to development of these techniques and how many defects are now identified that were previously passed along to downstream manufacturing steps and allowed to be assembled into the product. Additionally, it was unclear what impact the implementation of these techniques would have on product quality and cost.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- The collaboration is broad and deep, including huge corporations, startups, universities, and foreign governments. It would take a principle investigator like Ulsh to pull this off; certainly this is not a one-man show, but there is one person in the middle. There are many things happening, but there are also many secrets to keep. There is the necessity of keeping proprietary data safe and protected, as well as having a staff that understands the details of protecting information. Fortunately, NREL has established a facility where this can happen.
- NREL uses an excellent plan that includes laboratories, academia, and industry to explore concepts and quantify diagnostic abilities. The project seems to blend several disparate collaboration and technology transfer interactions (Small Business Innovation Research Phase 2, R2R consortium cooperative research and development agreement, Work for Others). This is commendable.
- The level of collaboration is the strength of this project. NREL is working with a membrane manufacturer, a fuel cell manufacturer, and a potential QC equipment manufacturer. NREL also has established meaningful collaborations with other national laboratories and universities, as well as two foreign laboratories.
- There is a good cross-section of partners, including industry, academia, and national laboratories.

- The project team has had much collaboration with industry and laboratories; however, more collaboration should be done with original equipment manufacturers (OEMs) that receive MEAs and build stacks. The team should screen existing manufactured MEAs and develop screening tools.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The contemporary fuel cell engine is pretty simple. There are no high temperatures, many plastic parts, and a performance that is better than that of an internal combustion engine. Even so, the engineering is demanding, and many issues needed solutions. This project was run parallel to the global effort of making continuous, timely advances. The project successfully addressed manufacturing issues. There is no question about relevance. There is obvious impact, but, as with all technical advances, it is always a team effort. Many advances are created simultaneously in different places because such advances result from smart people getting together. It is unclear whether NREL really was responsible. However, this one project certainly did have an impact on the technology.
- In-line diagnostics at high speeds are highly relevant, as noted by the several non-Fuel Cell Technology Office groups cited (Hydrogen and Fuel Cell Technical Advisory Committee, National Academy).
- The large-scale commercialization of PEMFCs will not occur without low-cost and high-reliability manufacturing, which will be possible only with appropriate QC tools. To this reviewer's knowledge, this project is the first major effort funded by the Office of Energy Efficiency and Renewable Energy that focuses on this critical need.
- The project has potential for some impact and relevance; however, it is not as significant when compared to many other projects.
- The improvement in manufacturing processes clearly has an impact on cost and performance. Given the difficulty in demonstrating a quantitative impact on these two metrics, it would be good to attempt to quantify the impact these various solutions can have on the immediate defect being investigated. It was unclear how many of the specific defects were previously produced (how these targeted defects were selected), what the scrap rate was or what the suspected quantitative impact on product cost or performance was, and what impact these processes would have if implemented.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- There are plans for the future. With the rapidity of technical advances, those plans can change. Hopefully they will change. What is proposed is solid and worthwhile, but timely action is also essential. Sort of like with an emergency room doctor, it is important to judge the project on what it does, not on what the project team proposed to do. It makes sense to give Ulsh and team a good amount of rope. This team has a good history of using freedom well, using freedom to make broad strides.
- The proposed future work is fine. A comment from last year's review suggests that more focus is needed. NREL seems to agree with this comment and plans to focus their future work now that their toolset has been established.
- Demonstrating a prototype system for in-line membrane thickness measurement is a key goal. Further study of defects on cell performance should be continued.
- Much future work was identified, and some priority should be placed to increase the relevance of the work. For example, the work on platinum-group-metal-free catalyst or anion exchange membrane manufacturing diagnostics should not be done. It is not even clear that these materials can meet performance targets. More work should be done to identify needs of OEMs that are building stacks.
- As the various portions of the project are technically proven, it is unclear how the project team decides if the process is useful and effective for solving a specific problem or need. For instance, the detection of pinholes seems to be well investigated by this team, but it is unclear what data the team has to validate the

usefulness of that work. Additionally, it is unclear if the team will continue to further develop this process or put it aside and move on to another manufacturing challenge, or how the next challenge will be identified and folded into the project. Given that it is very difficult to obtain detailed input from many industry partners, perhaps there is a way to garner confidential or anonymous defect data from industry to help steer the project to very well-targeted and highly relevant topics moving forward. The project team should let the data guide proposed future work.

Project strengths:

- The team has developed at least one process or solution that is being pulled to commercialization. This validates the applicability and purpose of the project. There are bound to be developments that do not prove to be useful, but if the team can continue and even improve its ability to garner information from many industry partners, the project will build in importance. Ensuring that the project is focused on real challenges with commonality among the industry may be one of the biggest challenges.
- The development of in-line diagnostics is needed by the entire industry. Development at a national laboratory for all to share is appropriate. The project has demonstrated a long list of accomplishments, and the progress is impressive. The work is methodical, quantifiable, and well-thought-out.
- Three project strengths were the quality of demonstrations, the level of collaboration, and the importance and long-term applicability of the work.
- The NREL team is excellent and experienced. They tend to focus on tough problems and make good progress.
- Many diagnostic tools were developed. The team has excellent capabilities.

Project weaknesses:

- Learning what is happening in the People's Republic of China would be a good addition to the NREL tasks.
- Data showing why these specific defects were investigated would help verify why the team has focused on them. It is not clear if these defects were the most frequent problems or if the performance hits associated with the defects were the top manufacturing-related problems. If the data are available, this should be stated, and the impact of implementing these solutions should be shown. If the data are not available, the project team should develop a means to obtain data to ensure future work is aligned with high-frequency defects, performance hits, or other challenges that are limiting the industry's ability to achieve cost and performance targets.
- There could be more feedback (discussed) from industry as to what kinds of defects are likely to be made by production equipment. There needs to be a final assessment as to the size and/or type of defect that affects performance. This is being done now, but there does not appear to be a distinct study of how small a defect that can still affect performance might be.
- The project needs a bit more focus on the key barriers "E" and "H" identified on slide 2, using existing manufactured MEAs, not MEAs that the team makes.

Recommendations for additions/deletions to project scope:

- The issue, of course, is not just the cost of hydrogen. Rather, it is the value added by the hydrogen system—i.e., a system that includes hydrogen and the things that hydrogen permits to happen. Today, refineries do not stand alone. Almost all of them are also electrical generators, converting waste heat into electricity, which adds much value to the operation. The next step would be looking at integrated operations, such as an "electrolyzer plus." The project team could consider several questions, such as the following: what operators do when the hydrogen tank is "full" (presumably they do not just turn it off); what options occur if prices are changed to match the market demand curve; what is to be done with the co-produced oxygen; and whether it makes sense to integrate a hydrogen generation plant with a sewerage system. As with any big capital expenditure, the real question is not cost but payback. If the hardware creates more value than the mortgage costs for that day, that is all that is necessary for success. Therefore, the real issue to address is whether, when a system is implemented, the overall system creates more value than the system's cost, regardless of what that cost is.

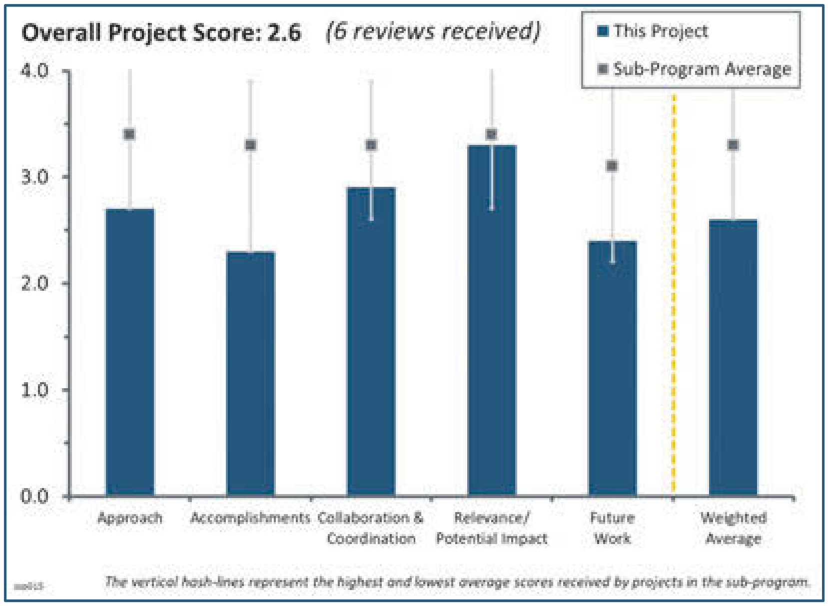
- The team should develop a list of types of defects and corresponding defect size that is determined to have a negative impact on performance. This list would then become a list of requirements for the diagnostic system to detect.
- The team should carry out more work with industry that builds stacks and study finished MEAs manufactured by others.

Project #MN-015: Continuous Fiber Composite Electrofusion Coupler

Brett Kimball; Automated Dynamics

Brief Summary of Project:

The objective of this project is to advance the state of the art for hydrogen transmission and distribution by improving the joining method that is used for piping. A composite-based coupler will be designed and tested, with the goal of achieving transmission pressure of 100 bar with a flow leak rate of less than 0.5% and a 50-year life expectancy for the part. To achieve this project's goals, work will focus on addressing three independent challenges in joining pipes: (1) tensile load through the coupler, (2) burst pressure, and (3) sealing of hydrogen in the pipe.



Question 1: Approach to performing the work

This project was rated **2.7** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The original approach of pursuing an all-non-metal coupler was innovative. This approach, however, has been abandoned because of an inability to meet long-term test requirements, specifically the fatigue test. A go/no-go decision in 2017 was not passed because the testing requirements were not met. To the company's credit, the project team appears to have worked with the Fuel Cell Technologies Office (FCTO) in detail to identify an alternative pathway and has received FCTO approval to pursue this pathway, even though the go/no-go was not met. The new approach includes metal components (though reportedly not in contact with hydrogen) but still has the benefits/impacts of not using O-rings and of enabling higher pressures.
- The hypothesis and original plan were strong and would have a significant effect on the industry. As is part of research, the project had to be re-scoped based on the results of the go/no-go milestones. The team members developed an alternative plan that seems reasonable and received a "go" decision from the U.S. Department of Energy (DOE). In the final year of the project, the re-scoped design will be evaluated and tested to the parameters approved by DOE.
- Automated Dynamics is well focused and practical for designing, building, and testing the new pipeline couplers.
- The original approach did not meet its go/no-go milestone. The new approach seems reasonable, but it has not yet been proven.
- The initial proposal focused on a novel coupling device for joining two lengths of polymer tubing that could transport hydrogen in a "pipeline." The contractor company was sold to a Swedish firm, and the firm changed the project so that it uses an already marketed coupler used today for natural gas pipelines. It seemed there was no purpose in continuing this activity.
- The approach is reasonable, but it seems to have a small scope of prototypes. While this is not inventing a new lightbulb, it appears that only a small number of options are being pursued for the budget.

Question 2: Accomplishments and progress

This project was rated **2.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- At the 2017 go/no-go decision point, the project had to be re-scoped owing to failure of the fatigue tests. A reasonable alternative was developed and approved by DOE. The team is currently developing the revised coupler.
- Progress has been delayed because of the inability of the original non-metal design to meet testing requirements, specifically the fatigue test. Accomplishments in the review period appear to be mainly related to a new design, as described in the Approach comments. From the very high- level information given in the slides, it is hard to understand how detailed or difficult the new design is, but this seems to be a small amount of progress overall for the year. It is good to hear that the new design is expected to be less expensive than the original design and that it will be able to leverage existing components and still have the benefits of not using O-rings and having higher pressure capabilities.
- The accomplishments are good. One would expect more options to have been covered for the budget.
- The presentation did not show any results from the original gadget. There was some concern about getting a longer-lasting seal, assuming that the natural gas tubing string could be successfully used for a hydrogen system. There was no convincing information given to assure reviewers of this.
- While the pipe can hold pressure, it is not passing the cycling test. The team has made some progress, but it is not clear what fundamental characterization has been performed to understand the failure. The team has laid out a reasonable plan for fiscal year 2018 to finish out the project.
- It appears the project did not make the December 2017 go/no-go criteria.

Question 3: Collaboration and coordination

This project was rated **2.9** for its collaboration and coordination with other institutions.

- The team is assembled of both industry and laboratory partners, which is a good mix for this type of research.
- It seemed that the new Swedish owner had expertise in pipe joining, and since that subject is of most concern, this change may be a positive one. There was no indication that the team had carried out any significant search for alternative couplings. There also was a suggested lifetime for the entire tubing string of 10 years, which is not a very interesting trend if one has to write off the capital expenditures on a 10-year basis. This adds to the cost for moving hydrogen around. There was no mention that a natural gas tubing string has such a short lifetime.
- Expertise from the other partners was well described and relevant to the project. Savannah River National Laboratory’s involvement appeared to be limited to understanding the ASME requirements and testing. It was not clear whether any partner on the team has failure analysis expertise to understand the mechanisms for failure.
- Collaborators provide market/commercialization, guidance/expertise, and materials/testing expertise. It is not clear, overall, what the market could be for Automated Dynamics’ work. Perhaps this could be provided from the FCTO cost modeling, or another collaboration might be appropriate.
- Automated Dynamics does have national laboratory and industry collaborators, but it is not clear who is doing what on the project.
- Automated Dynamics’ collaborations may benefit from including work with folks in the gas industry.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is a significant question that needs to be answered, as the potential of implementing plastic pipes for the transport of hydrogen is a cost-effective alternative that may achieve market penetration. A stable, non-metallic coupler will be required for widespread application.
- This project is very important to reducing the capital cost of installing hydrogen pipelines. Early market hotspots are expected to need such a solution in a near timeframe.
- Hydrogen transportation is a key issue/enabler for infrastructure.
- Good couplers on high-pressure pipelines are a requirement. However, it remains unclear whether couplers are a major technical roadblock to automotive hydrogen fuel commercialization.
- When discussing a hydrogen economy, distribution issues are obviously brought up. There are only two options. You can make hydrogen, using something like electricity at the point of use, or you can make it elsewhere and distribute the hydrogen to where it is needed. Transportation will obviously play a role. Therefore, distribution systems for hydrogen gas need to be understood. There is nothing more important than the tubing or piping. It is disappointing that the hype of last year has gone away. The carefully designed, electrically heated sealant was eliminated. Rather, a threaded compression fitting has moved into a "first choice" position. It seems like the project has concluded.
- It is not clear what the potential market is for the work. It is currently unclear how much hydrogen pipeline is expected to be installed and what the potential financial benefit of this technology might be. Nothing was stated in the presentation about how this technology may impact FCTO's plans with regards to H2@Scale or the buildout of a hydrogen pipeline. Perhaps this information was included in initial Annual Merit Review presentations, but it would be useful to provide at least high-level reminders with any status updates, given new FCTO targets or developments. The information provided on the relevance slide did not really address relevance to FCTO objectives or needs.

Question 5: Proposed future work

This project was rated **2.4** for its proposed future work.

- The proposed future work is to test the revised design. This was approved by DOE and seems to be reasonable and acceptable.
- Multiple prototype fatigue tests may be prudent to get a sense of reproducibility and variability.
- Proposed new coupler designs need to be tested.
- Required future work is pretty clear, given the status of the project, assuming that the new design can pass the fatigue test. Other activities mentioned, such as commercialization and cost evaluation, should obviously be undertaken after a successful go/no-go decision based on the new design passing the fatigue test.
- There was no future work discussed, which left the impression that the new company owner, a Swedish firm, expressed no interest in continuing the work, so future work was not all that apparent. Even so, the questions remain about whether the coupling device, a threaded plastic device, works with the smallest molecule, hydrogen, and whether the leakage rate will be acceptable. The question-and-answer session indicated that the tubing, which may be able to contain hydrogen, is available in 1 km spools. Therefore, a 50 km tubing string has 100 joints that could possibly leak, one from the incoming pipe and one from the delivery pipe on each coupling. It seems like getting an acceptable leakage rate will be a challenge.
- The proposed work basically involves trying to fatigue test again and iterating until the design passes. The team should outline what parameters could be changed to make the design more robust and, if needed, the reasonable number of iterations before deciding whether the solution will work.

Project strengths:

- The principal investigator addresses a stated FCTO barrier for pipelines and brings together a team that can address design and manufacturing, commercialization, and materials and testing. The output of this project (i.e., a coupling solution without O-rings that is capable of higher-pressure operation), if successful—even with the design change—appears still to be of value to DOE. The team had the ability to address the failed fatigue tests with a new design.
- The team was agile in revising the design after the go/no-go decision. The new design still shows promise and will help the industry if successful.
- Automated Dynamics produced well-focused and targeted work that designs, builds, and tests prototypes.
- The project team has tried to regroup after a failed test and took initiative to perform a redesign on the component between funding periods.
- The team has experience with composite piping.
- Automated Dynamics is working with a competent company, although no description was given about the quality of the new owner.

Project weaknesses:

- The failed fatigue test was an unwanted result, but a significant amount of research involves failure. If the new design does not work, it may hinder the widespread use of plastic tubing for hydrogen transport.
- The relevance and cost–benefit of the project are not clearly stated, which is especially relevant to H2@Scale. The original design did not work. This, in and of itself, is not a weakness, but the new design must be shown to be able to pass the fatigue test for additional efforts to be supported.
- The overall relevance/impact of the project is unclear.
- It is not yet clear that the team has a concrete plan to pass the test if the first iteration does not work.
- It is unclear whether the funding is congruent with the presented effort.
- There are no obvious successes. The questions about sealing hydrogen tubing strings remain unanswered.

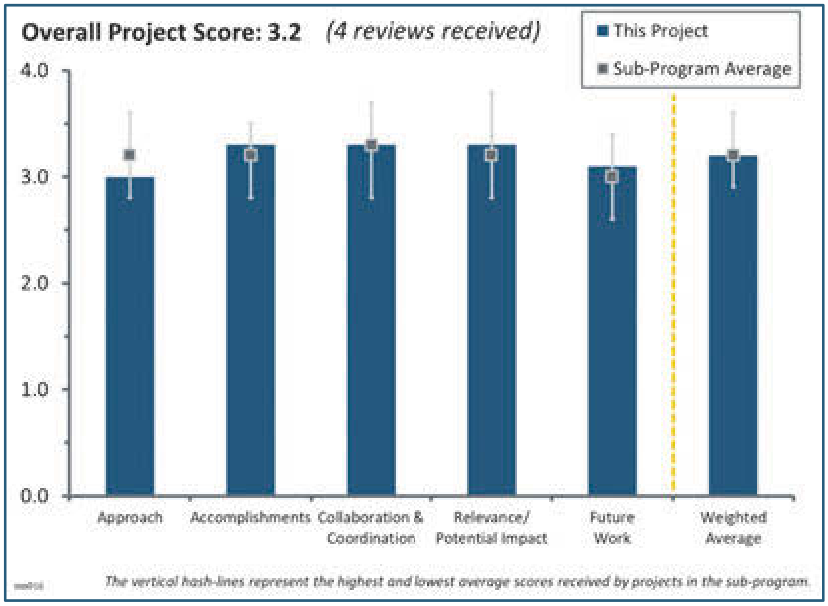
Recommendations for additions/deletions to project scope:

- The revised task plan seems reasonable for the amount of time and funding left on the project.
- The commercialization effort should be supported only if the new design passes the fatigue test. If this success is achieved, it seems that a cost evaluation will be very useful (as indicated in the Future Work), which should be done in tandem with or informed by any relevant FCTO/H2@Scale/H_2 Delivery analysis, cost modeling, etc.
- Automated Dynamics should increase the number of design options or produce variants on prototypes ahead of testing cycles. These options could include the testing of multiple durometer O-rings, varying the length of fused materials, and others. In such a way, reliability trends can be obtained in a shorter timeframe. A single-point prototype is not as informative as a suite of prototypes.
- It seems that this project has concluded. The initial novel coupler was not moving forward, and the problem remains. Perhaps the issue might be resolved by some work that determines the quality of coupling that can be achieved by the alternative hardware. However, it remains to be seen whether that will be good enough, i.e., whether the suggested quick fix will really work or what the diffusivity of hydrogen will be through the tubing. Certainly, other people must be using polymeric tubing for hydrogen piping.
- Automated Dynamics did not meet its go/no-go decision point in December 2017.

Project #MN-016: In-Line Quality Control of Polymer Electrolyte Membrane Materials

Paul Yelvington; Mainstream

Brief Summary of Project:



With the goal of improving the reliability and reducing the cost of automotive fuel cell stacks, this project seeks to improve in-line quality control technologies that are used in the manufacture of polymer electrolyte membrane (PEM) materials. To achieve this goal, the project team will build a prototype system capable of simultaneously measuring defects in a moving membrane web and membrane thickness over the full web width. The developed system will scan the manufactured membrane with 100% coverage, marking and logging defective regions.

Question 1: Approach to performing the work

This project was rated **3.0** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The Mantis Eye approach to defect detection is excellent. The approach to validating the technology and the partner institutions is also excellent.
- The investigated approach is appropriate for addressing the main barriers and reaching the technical targets.
- This only missing component of this project is the involvement of membrane/membrane electrode assembly (MEA) manufacturers.
- Mainstream Engineering Corporation (Mainstream) has built an inspection station and systematically evaluated its capability. That said, there have been no demonstrations executed with potential commercial customers, and there is no evidence presented that suggests that commercial customers were consulted during the design of the inspection station.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Mainstream has demonstrated excellent progress in the development of the detection technology and in real-time image processing. At this point, the technology may fill a gap identified by membrane/MEA manufacturers and help meet DOE's goals, but improved resolution would make it a definite benefit.
- The project is moving along.
- Progress is good regarding the defect detection and the thickness determination, in particular with increasing web-line speed. Results on the impact of defect size on durability would have been appreciated.
- The inspection station has been built and qualified. This could become an important quality control (QC) tool for membrane manufacturers, but without input from membrane manufacturers, it is difficult to assess how valuable this QC tool will ultimately be.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- There is excellent and obvious collaboration with the National Renewable Energy Laboratory (NREL) and Georgia Institute of Technology (Georgia Tech). These two organizations provided the samples and coating lines for the implementation and testing of the Mainstream detection technology.
- The collaboration between Mainstream, NREL, and Georgia Tech appears well coordinated.
- It appears that all partners are participating.
- There appears to be good interaction with NREL and Georgia Tech in this project, but there was no engagement with membrane manufacturers during the design and validation phases.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is relevant to the goals of the Fuel Cell Technologies Office. Inline defect detection is critical to roll-to-roll processing to ensure a concurrently lower scrap rate, no over-quality, and thus a lower membrane cost.
- There is a high degree of alignment with Program goals, assuming this form of QC addresses manufacturer needs.
- The intent of the project—to build and qualify an inline QC tool for membrane manufacturing—is extremely relevant to low-cost PEM fuel cell manufacturing. The relevance score would be much higher with an increase of earlier involvement by potential end users to ensure that the product being developed will be commercially accepted.
- NREL conducted beginning-of-life (BOL) fuel cell performance tests on cells with varying size defects and determined that 40-micron defects cause problems with cell failure, while 10-micron defects do not. This led to the conclusion that the current hardware detection limit of 25 microns is adequate. However, while defects smaller than 40 microns may not be an issue with BOL performance, such defects may lead to premature cell failure during operation. Even defects smaller than 10 microns, which Mainstream indicates are possible with the current hardware and the use of multiple cameras, can be expected to cause premature cell failure due to gas crossover and the resulting product heat. An analysis and/or discussion of the spatial resolution limitations of the technique is necessary, as is an analysis of the cost of the system as a function of resolution, to determine the full potential and impact of this technology.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The future proposed work appears appropriate for achieving the project's targets. The demonstration of the prototype system for industry consumers is very important. The quantified results of the defect size on the durability should be presented as a cost analysis.
- It is critical that the commercial demonstrations are executed as stated in Mainstream's plans.
- Improving the defect resolution to 10 microns in the remaining two months of the project is a good start toward demonstrating the full utility of the technique. However, an analysis of the spatial resolution limitations of the technique and an analysis of the cost of the system as a function of resolution are needed to determine the full potential and impact of this technology.
- It is difficult to tell what decision points have been implemented.

Project strengths:

- The main overall project strength is the ability of the team to provide real-time detection and spatially resolved digital marking of the location of defects within the entire membrane width. The collaborations with NREL and Georgia Tech to test and validate the technology are also strengths.
- One of the project's strengths is the successful design and construction of an inspection station to identify membrane defects. The qualification of the inspection station by finding multiple types of defects is another strength.
- The Mainstream engineering team's association with the NREL team is of high value; the association will speed up the development and the validation of this kind of technology.
- The project is targeted at reducing defects and, therefore, reducing failures and associated costs of fuel cells.

Project weaknesses:

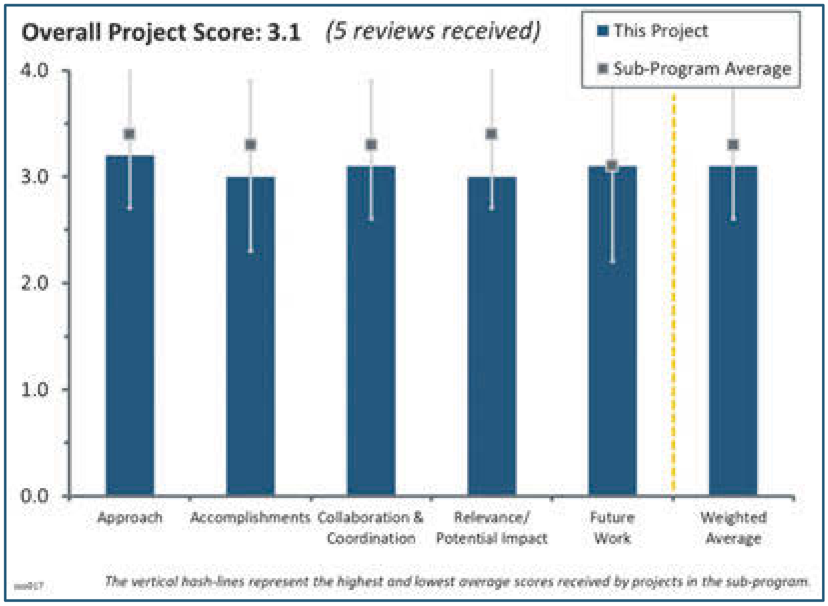
- Collaboration with a membrane manufacturer would strengthen the project. The project team focuses only on membranes for fuel cells. Perhaps the team could also look at other applications, such as PEM electrolyzers.
- There is a lack of input from potential customers during the design of the inspection station. No commercial demonstrations have been executed yet (although two are planned).
- The lack of pull from the market raises concerns about the actual need of this technology.
- The main project weakness is the demonstrated current detection limit of 25 microns.

Recommendations for additions/deletions to project scope:

- It is recommended that the project team add an analysis of the spatial resolution limitations of the technique, as well as an analysis of the cost of the system as a function of resolution. These analyses are necessary to determine the full potential and impact of this technology.
- The project team should investigate the application of this technology to PEM electrolyzers. Also recommended is an investigation of the effect of defect size, not only on performance but also on durability.

Project #MN-017: Manufacturing Competitiveness Analysis for Hydrogen Refueling Stations

Margaret Mann; National Renewable Energy Laboratory



Brief Summary of Project:

This project contributes to manufacturing cost analyses for major hydrogen refueling station (HRS) systems. National Renewable Energy Laboratory (NREL) will work with the Fuel Cell Technologies Office to establish HRS manufacturing cost models and a manufacturing cost framework to study costs of HRS systems, including the compressor, storage tanks, chiller and heat exchanger, and dispenser. Investigators will assist in highlighting potential cost reductions in the manufacturing phase for future research and development projects in this field.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- NREL methodology is solid, with good economic engineering. The project sought out good partners and looked at most of the important issues.
- NREL does a good job of analyzing the electrolyzer HRS.
- This is a concise, tight approach to performing the bottom-up manufacturing cost analysis.
- The proposed approach is correct.
- NREL completed a comprehensive assessment of manufacturing costs of polymer electrolyte membrane (PEM) fuel cell electrolyzer systems, which enabled realistic comparisons with commercial alkaline electrolyzer systems. The approaches for completing this assessment were sound, although it would have been helpful if the cost analyses could have been quantified on the basis of hydrogen cost and not system cost. Also, cost-reduction opportunities for PEM fuel cell electrolyzer systems were identified but not quantified. An ultimate recommendation on the potential of either approach to meet the U.S. Department of Energy's cost targets was not provided.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- NREL has made significant progress from the previous year. The team has put together analyses on both PEM and alkaline electrolyzers, and it has outlined the detailed supply chain needed for the industry.
- The detailed study of HRS supply chains is well done and highly useful. Although the current market volume is modest, it is growing, and it has now become large enough to mature into a global business. Although this suggestion is outside of the charter, it would be interesting to have explored International Organization for Standards (ISO) standards to determine whether existing design and manufacturing

standards are regional or global. Although this is also outside the charter, it would have been interesting to explore early technical failures and early accidents. (It is easier to fix stuff before you build it.)

- This assessment is important for DOE to determine whether future investment in PEM electrolyzers is warranted. The analysis was thorough, and a good deal of information was obtained and compiled into a very thorough assessment. NREL stopped short of providing a quantitative conclusion regarding the commercial viability of either alkaline or PEM electrolyzer systems for HRSs.
- NREL completed a detailed analysis of electrolyzer system costs for the generation of hydrogen at a refueling station, but the costs associated with the rest of the dispensing systems, the hydrogen storage systems, and the real estate analysis were missing. Furthermore, it should be in the scope of work to conclude how many HRSs would be needed to re-fuel a significant portion of the passenger vehicle fleet.
- The reviewer provided the following comments:
  - The presentation focuses this year mostly on the onsite hydrogen production. It is not clear whether onsite hydrogen production is considered production linked to HRS systems only or any onsite production.
  - The HRS activity was reduced to an update of the global HRS trade flows. Unfortunately, there were some mistakes in those efforts. It is quite surprising to see that European HRS systems are mostly important HRS systems, whereas there are plenty of European HRS suppliers who are delivering HRS systems in the framework of European projects. Using the same color for importing and unknown suppliers leads to confusion and must be avoided. The two must be distinguishable. Moreover, the numbers for France are incorrect. At end of 2017, there were 19 active HRS systems, and more than 10 are planned. For the number of HRS systems planned in Europe by 2025, the project team should have referred to the Alternative Fuel Infrastructure Directive published by the European Commission last year. These numbers represent a commitment to the minimum number of publicly accessible HRS systems that should be deployed by 2025.
  - The table for comparison of the alkaline and PEM electrolyzers lacks precision. The system price is given in dollars per kilowatt, but the power range is unclear. The operating pressure should be given because it has an impact on system efficiency, and the expected operating hours should also be included when providing system durability information.
  - The tables presenting the key performance indicators (KPIs) of the PEM and alkaline electrolyzers should use the same KPIs. For instance, the hydrogen production rate, operating pressure, and temperature are missing for PEM electrolyzers. There is a mistake between Pt-Ir and platinum-group-metal-loading values. For PEM electrolyzers, the given values seem very optimistic (1.619 V @1.8 A/cm² if 80°C at 1 bar is assumed), in particular when considering a Nafion 117 membrane.
  - The rationale for 385 kg_{H2}/day for a 1 MW PEM electrolyzer should be given.
  - On slide 15, the system cost presented is around \$500/kW, whereas in slide 6, the system cost in the table was \$1,570/kW. It is unclear which number should be considered.
  - The AC/DC rectifiers are presented as very expensive, but when connected to renewable energies, a DC/DC converter might be sufficient. It would be interested to know how this could affect the overall system costs.
  - Slides 38 and 40 present the global electrolyzer producers. Important global players are missing. It is really surprising not to see Nel Hydrogen, the biggest alkaline electrolyzer manufacturer and also the new buyer of Proton OnSite. McPhy is also missing. Regarding PEM electrolyzers, the United Kingdom's ITM Power is missing.
- On slide 39, presenting the polarization of commercial PEM electrolyzers is not enough. Gas permeation should also be given, in particular when targeting an increase of the operating pressure (30 bar) to increase overall efficiency. Therefore, a figure presenting $\%H_2/0_2$ versus the current density should also be presented.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- NREL has several strong collaborative partners, including domestic and foreign-based ones, along with private-sector partners and laboratories. Collaborators include E4tech from the United Kingdom, Forschungszentrum Julich (FZJ) from Germany, and three industry partners: AEG Power Solutions, Magna-Power, and Grundfos. The PI calls them collaborators, whereas slide 21 just states that these organizations provided cost data for the electrolyzers.

- Having collaborators from three other national laboratories makes sense because parallel studies are under way and because computer approaches exist to manage data. The project is almost complete. There was no description of "who did what," so most likely NREL built a multi-laboratory team, and the results flowed from that.
- The level of collaboration was commensurate with the objectives and needs for this analysis.
- Industry partners would be useful for the collaboration. In fact, many of the electrolyzer system original equipment manufacturers would understand the project team's system costs, even at the 1 MW scale under study.
- Collaboration and coordination efforts seem correct, but more connections with industry or international bodies would have been needed, in particular for the HRS mapping.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Current times dictate that hydrogen will prove useful as an energy carrier and energy-storage medium. Electrolyzers are old technologies. Typically, they have been built in low volumes and purchased by organizations that had no cost constraints, like the U.S. Navy. We now anticipate large markets for hydrogen-generation hardware, and the economic gain is changing. Hydrogen refueling is a new art, and that industry is just beginning. Initial costs for refueling stations are high, and costs need to come down. This project gives a snapshot of where we are in 2018, and it itemizes the parts requirements, making it easier to direct efforts to bring costs down.
- This work is highly relevant. The results could be used by both policymakers and manufacturers that are trying to be cost-competitive. These results could help shape future cost targets for both component and system costs. The results could support the future work of H2@Scale.
- The project should have studied the refueling station costs more, as well as studying those costs relative to the entire passenger vehicle fleet. No cost targets were identified, so it is difficult to gauge the relevance/impact. For example, dividing the cost of all the current gasoline stations by the number of gasoline cars provides a number for the refueling station cost per vehicle. A similar number could be calculated for the HRS scenario. DOE could establish a target for such a metric, and the project could determine how far the technology is from the target.
- This project aims to provide an assessment that will inform DOE of the viability of PEM and alkaline electrolyzers for HRSs and to identify areas for investment to improve viability. It would have been helpful to see more definitive conclusions, which would provide more value to DOE in building its future project portfolio.
- The data provided will be useful for better understanding the United States' strengths and weaknesses in HRS and onsite electrolyzer manufacturing. However, to be really efficient, pointed imprecisions and mistakes should be corrected.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The project ended in June 2018.
- It is not clear that this project is continuing, but the stated future work areas are appropriate. Also, if the project continues, it would be interesting to include an assessment of high-temperature (solid oxide) electrolysis systems and how they compare to PEM and alkaline systems.
- There is proposed future work to complete the task—which is almost complete—and to continue exploring "emerging" technologies; this is all good work that needs to be done. What seems to be missing is the "innovation" piece and some understanding about how the really large investments in fuel cell technologies

can support both innovation and cost reductions in electrolyzer technologies. Issues such as hydrogen safety are entirely parallel, and much of the materials science for fuel cells will be valid for electrolyzers. Therefore, there is a solid technical base, and electrolyzer technologists do not have to reinvent. That will save capital and time.

- NREL should complete manufacturing cost analyses of onsite hydrogen production and PEM and alkaline electrolyzers. The project team should also study the cost effects of emerging manufacturing technologies. The team should also look at economies of scale for hydrogen production systems and the impact on both capital costs and production costs. The team should also study the change in capital expenditures of hydrogen production. The team should benchmark its results against new hydrogen installations.
- The proposed work is appropriate, but pointed imprecisions and mistakes in the global surveys should be corrected. Moreover, the impact of the electrolyzer operating pressure, the stack lifetime versus performance, should be better taken into account regarding the whole onsite hydrogen production HRS system.

Project strengths:

- The main strengths were to map the HRS flows globally and then to investigate the United States' strengths and weaknesses to favor the domestic industry.
- This is an important project to study the various refueling station costs.
- The project team used a sound approach for its cost analyses at the component and system levels.
- The team collected considerable data and organized the data in sensible ways.
- Thorough research was conducted that can support policymakers and industry.

Project weaknesses:

- The cost numbers are for stand-alone hardware rather than for systems. This is akin to estimating the cost of a jet engine rather than the whole aircraft. Electrolyzers usually make byproduct oxygen, a valuable substance. A large refinery like the Exxon complex in New Jersey, which includes one of the nation's largest electrical generation stations, is based on waste heat, and doing the numbers that are essential requires a system analysis.
    - Electrolyzers are somewhat inefficient, and there is a good heat flux that needs to be considered. So there are capital and operating expenditures. As with any energy facility, the real economic analysis is simple: the company borrows money, and the bankers want recovery: principal plus interest. That adds up to so much each month. If you get more income than that number, that is good; if not, that is bad. An analysis that focuses only on the "costs," i.e., what a manufacturing company can extract, does not address the real issue. It is good to know the bad news. Electrolyzers do have costs. It is also necessary to understand that nations tend to barter (for example, Russia is providing petroleum to China in exchange for high-speed trains), and in those cases, actual costs are never known accurately. Perhaps a deeper dive is necessary.
- The project team has shown some imprecisions in the survey analysis of HRS flows and electrolyzer manufacturers. This may affect the outcomes and recommendations from the project.
- More comparison studies should have been conducted with respect to gasoline stations.
- The project lacks definitive conclusions.

Recommendations for additions/deletions to project scope:

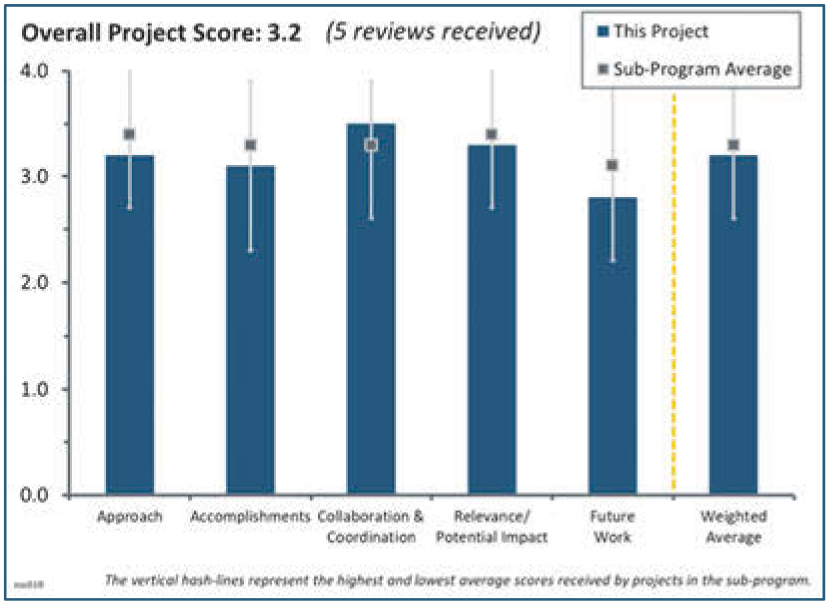
- The scope seems appropriate for the amount of funding and will provide valuable information to the research community and industry.
- It would have been interesting to look at some of the federal hardware, for example, the "oxygen generators" deployed on U.S. submarines. There are also hydrogen generators, which are used for cooling bearings in generators. This hardware, to some extent at least, is "commercial."
    - Siemens is selling an interesting fuel cell submarine, designed to submerge and remain underwater for long periods. Certainly, there is an oxygen generator in that hardware, as well. These military devices may cost even more than is suggested. However, they have unique specifications. Submarines are prone to be depth-charged, resulting in very high G forces, so the

hardware needs to be unusually robust. Certainly, a hydrogen leak into a submarine would be an event to avoid, so these are probably "excessive" safety features.
    - There are some things to be learned, and they need to be part of the NREL intelligence. It is not yet clear how much safety considerations influence cost and whether the existing standards are good enough for "general public use"—in other words, what protective protocols are necessary to ensure protection against a person with evil intent.
- It is not clear what the impacts are—if there are impacts—of onsite hydrogen production electrolyzers on an HRS with the rest of the electrolyzer production. Regarding the cost analysis, the main differences mentioned between countries are explained by labor and energy costs. The assumption of comparable materials costs is not as obvious and should also be considered more precisely. For instance, the costs of membranes in the United States, Germany, and China may differ significantly.
- The project has ended.

Project #MN-018: Roll-to-Roll Advanced Materials Manufacturing Lab Consortium

Claus Daniel; Oak Ridge National Laboratory

Brief Summary of Project:



All U.S. Department of Energy (DOE)-sponsored cost analyses for high-volume production of membrane electrode assemblies (MEAs)/cells assume roll-to-roll (R2R) processing will be used. The project objective is to develop R2R manufacturing techniques to reduce the cost of automotive fuel cell stacks at high volume (500,000 units/year) from the 2008 value of $38/kW to $20/kW by 2025. The project goals (depending on technology area) are to (1) increase throughput by 5x and reduce production footprint, (2) reduce energy consumption by 2x, (3) increase production yield by 2x, and (4) enable a substantial shift of manufacturing to the United States by assisting in the development of a domestic supply chain.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This project is aimed at developing R2R manufacturing techniques to reduce the cost of fuel cell stacks at high volumes by understanding and optimizing the process and material parameters. The project team's approach is promising, with a focus on MEA fabrication and testing, as well as the characterization of gas diffusion electrodes (GDEs) and inks to explore the process parameters. The team accomplishes this by leveraging various unique capabilities and expertise across multiple national laboratories.
- The proposed approach is correct, with the presence of complementary competencies (i.e., manufacturing, testing, characterization, and modeling). Focusing on MEA production, and in particular GDEs, is indeed crucial to reach DOE performance and cost targets. It is appreciated that the targets have been quantified.
- This project includes a well-put-together approach of the consortium and the research, involving both industry and laboratories. Setting up the cooperative research and development agreements (CRADAs) to get industry support is an effective way to move the research along.
- The team quickly identified a lowest-cost manufacturing approach. However, the team also focused much effort on the fuel cell testing of finished MEAs from manufacturing efforts.
- It is true that R2R manufacturing has considerable applications in fuel cell manufacturing, but even so, as in all manufacturing, one first has to know the raw materials and structures to be made with the manufacturing procedure. The project is based on improving (including lowering the cost of) technology that is already in use. The procedure is thoughtful but not that unique. The goals are clearly defined. A competent, durable team has been assembled. There is careful analysis. The emphasis on "[enabling] the United States to capture a substantial portion of R2R opportunity" may not be that realistic. Perhaps it should have read "a significant portion," realizing that 10% of a large number is a large number.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The results presented are of high quality and have been well explained. The team has confidence in the high potential of using R2R to produce catalyst-coated backings (CCBs), which have several advantages over catalyst-coated membranes (CCMs). The main parameters of the ink preparation have been taken into account and their respective influences noted. Finally, the performance obtained is comparable to the standard spraying process. There is a good balance between technological achievements and the comprehension of the physical mechanisms. This is important because, depending on the future MEA properties that industry will seek, the process parameters, the materials used, and the composition of the ink will have to be adapted.
- There are efforts to shift manufacturing in the United States by enhancing supply chain capabilities.
- The team has made good progress on several aspects of the project related to the goals, in particular, the mass activity achieved with the R2R electrodes (with an ionomer overlayer), 3D imaging with ionomer and pore distributions in the GDEs, and characterization of inks (as in viscosity and ultra-small-angle X-ray , USAXS). These investigations should be extended to explore the influence of the ionomer overlayer, as well. These results are definitely interesting, and the accomplishments stand out as a comprehensive investigation on the characterization of materials used in or produced by R2R manufacturing. For what the team has tried to accomplish, the results are promising, although a bit more characterization-focused. While the relevance of the results to the project is explained for certain tasks, the overall relevance to the objectives could be stated more clearly. Similarly, the modeling efforts, or their contribution/connection to the other findings in the project and process optimization, are lacking. Moreover, the team's accomplishments are well explained and coordinated, given the number of partners.
- The technology is still in flux, and details are critical. There is much opportunity for new ideas. The principal investigator (PI) discussed the pros and cons of the R2R versus CCM selection. Various manufacturing options are explored. The accomplishments define specific procedures, such as the "ink studies" formulation, mixing, and rheology, for example. This is all good information, but a wide range of combinations exist. Progress is certainly evident, but even so, the task is difficult. There are many variables, and assuming that one particular route is the optimum one will prove difficult. The essential task of MEA characterization is done by the National Renewable Energy Laboratory. Certainly, much of the good, hard work has been accomplished. How much of this will lead to a successful manufacturing engineering protocol remains to be seen. In short, there is good progress. The project seems to be on track.
- The team should analyze different manufacturing approaches and their impacts on overall costs, for example, the effects of solvent casting versus water-only casting in the catalyst ink. The PI mentioned advantages of casting ink directly on the gas diffusion layer (GDL). However, the advantage of casting ink on liner is faster line speeds; GDL line speeds will be limited.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- The project's collaboration is excellent; the project has multiple laboratories and industry partners, and it is set up in such a way that it has the ability to grow the partner membership.
- The project seems well organized and has collaborated with many partners. The contributions from each partner are clearly stated, but the coordination between different partners (i.e., national laboratories) could be improved or better explained. A flow diagram showing the information/sample flow would be very useful.
- All laboratory-based collaboration was excellent; however, while collaboration with industry partners was identified, no results were presented.
- Project coordination appears efficient regarding the results obtained during this first year. Each academic partner has a well-defined role. Collaboration with projects from the Fuel Cell Consortium for Performance and Durability (FC-PAD) and the Electrocatalysis Consortium (ElectroCat) would be welcome. Collaboration with industrial companies producing MEAs for polymer electrolyte membrane fuel cells

(PEMFCs) should take place next year, as the composition and structure of the CCBs for fuel cells and CCMs for electrolysis are not the same. The role of Eastman Business in the project is not clear at all.
- The staffing is drawn from four national laboratories and two small companies. The laboratories have acquired quality facilities and good people. The separation of tasks seems complete and appears credible but arbitrary. Industry leaders are not part of this. This is the usual concern where who the customer is and who gets to use this technology is unknown. Also ambiguous is what "part" is being "manufactured." Whether the supplier supplies the membrane, the ink, or the complete MEA is also not known. The 5,000+ fuel cell cars in California have working fuel cells, which all have large quantities of manufactured MEAs; it is unclear how this project interacts with that already-in-place supply chain.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The main objectives of the project are to reduce the cost of automotive fuel cell stacks at high volume (500,000 units/year) by improving and optimizing R2R manufacturing techniques. These objectives are directly relevant to the key cost/volume targets set by DOE; the project goals align very well with the DOE objectives. If successful, this project will make important contributions to addressing issues of cost for fuel cells.
- Focusing on the manufacturing of the active layer is really relevant to achieving DOE's performance and cost targets. As presented in the cost analysis of Brian James and, in particular, the sensitivity analysis, power density and catalyst charging are the most critical parameters. In addition to the ongoing studies of the active layers, this team is investigating their manufacturability using the most usual production means. To ensure a high impact, the team may further investigate the current compositions of active layers for fuel cells and electrolyzers, and also investigate the new active layers developed in laboratories.
- This project has high potential impact; improving the R2R manufacturing process could significantly reduce the cost of production in the fuel cell/hydrogen generation industry. This could lead to significant gains in U.S. manufacturing.
- The MEA is clearly at the heart of the technology. The rest of the fuel cell system is designed to establish reaction environments that result in appropriate conditions for excellent MEA performance. There could be nothing more relevant. Even so, there is a manufacturing technology in place, and this activity seems to ignore that fact. Siemens is installing PEMFCs in the submarines they are selling in global markets. If existing players are experiencing problems with MEA manufacturing, that fact was not presented. This project may well be adding value, but there was nothing described that might suggest that was or was not happening.
- It is unclear what the relevance or impact of DOE funding on this Technology Readiness Level 8 work really is. This project should be industry-funded.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- In addition to the proposed work, it would be interesting to investigate the impact of viscosity on the coating speed and the impact of water content and coating speed on the electrode structure after drying. Some complementary (nano) characterizations of the electrode structure (with the Oak Ridge National Laboratory, for instance) would be interesting to view (i.e., the obtained structures and morphologies, depending on the process parameters) and to compare with the state-of-the-art (SOA) MEAs.
    - This investigation would also be useful to validate the foreseen modeling activities.
    - In addition, only single current–voltage (I-V) curves have been presented. Some durability tests should also be investigated and completed with (nano) characterizations in cooperation with FC-PAD. The team may also investigate new active layers developed in laboratories.
- There is future work with additional inks and coating. Modeling work would also be required.

- The details of future work are not described. The way forward is not all that clear. The project's future work is hard to evaluate.
- The proposed future work tasks are vague and not descriptive. It is not clear what will be accomplished and how it aligns with the overall project goals.
- Future work should focus on collaboration with industry partners.

Project strengths:

- The coordination of the project, the defined role of each partner, and the competencies of the people involved are real strengths. In particular, the fact that some of them are also working on deposition of electrodes for batteries can facilitate the development phase for fuel cell electrodes.
- The individual laboratories' focusing on each laboratory's specialty is a significant strength. The ability to grow this project through CRADAs is an effective and beneficial way to have a return on investment of the DOE's cost share.
- The project leverages expertise across the laboratories to bridge manufacturing and advanced characterization. The team is able to carry out a wide range of tests and characterization studies.
- There is a good focus on manufacturing methods that are low-cost, as well as good progress on linking manufacturing parameters to fuel cell performance.
- This project has great people. The laboratories and manufacturing sites are well equipped. The modeling abilities are good. This is a winning team doing very good stuff.

Project weaknesses:

- It seems like the very good results presented here are on the same pathways, using the same techniques, and using equally qualified staff as others who are doing fuel cell research and development. It is good to have a team with a "manufacturing focus," even though one could argue that that emphasis has really been at the center of the DOE's focus for decades. An example is the continued emphasis on "lowering the platinum loading," a leading subject beginning in 1980 and continuing to current times, which has also been about cutting costs. However, as to the goals, the people, the facilities, and the results, there is no question; there is not a weakness to be seen.
- The main weakness of this project is the lack of visibility for industrial interests and transfers. The only one mentioned this year was considering an electrolyzer using only CCMs, whereas the focus has been put on CCBs.
- The future work plans lack details as to what will be accomplished and how the plans will help the overall project's goals on cost reduction. Some of the contributions from the laboratories (e.g., simulations) are not clear.
- It is uncertain what the real focus of this project is, or what the targets or goals are.

Recommendations for additions/deletions to project scope:

- It seems like the time has come to get to standards. One useful route might be for some combination of laboratories to come up with a plan (perhaps done in-house, perhaps farmed out to a contractor) to create, manufacture, and distribute "certified" (down to the source of the platinum) reproducible test specimens. The MEAs are sort of standard. This would lead to some meaningful tools. For example, someone working on new concepts could say that "our product is 1.17x that compared to the DOE standard." There also should be new rules that require all DOE contractors to report standard error. In other words, each published measurement is the result of three or five individual and totally parallel experiments, and then those results show error bars. This presentation is a good example of what is needed. There is a polarization curve, and then a second, obviously better. It looks good. But it is uncertain that that can be done twice with the same result. It is not clear that the "existing" result is correct (so the new data is really better) or simply better than a bad result. It is time to address this data issue. Of course, in the end, suppliers will necessarily sell products with certified performance specifications. Such a plan would give clear, definitive specifications to those who want to enter the parts market. That sort of discipline can save years of frustration and error for a willing, smart company.

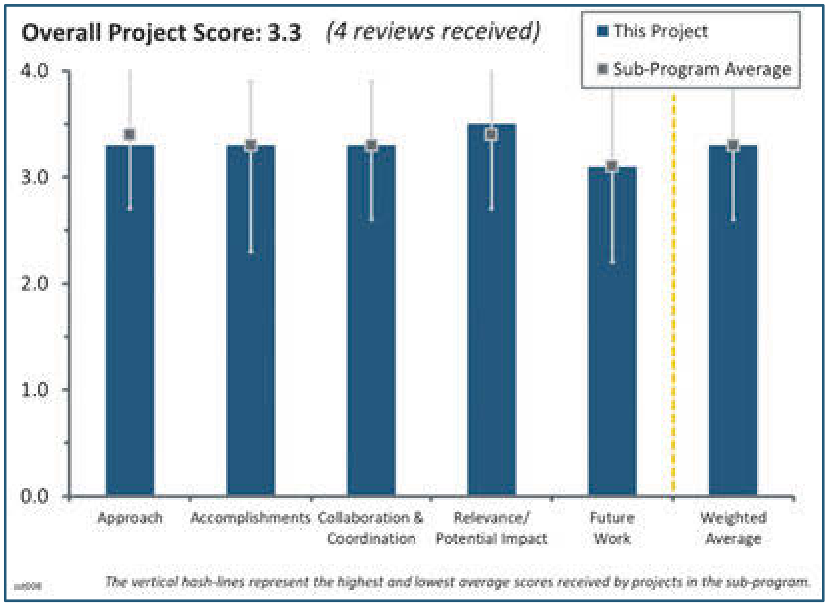
- It would be interesting to conduct complementary (nano) characterizations of the electrode structure (in collaboration with FC-PAD) to view the obtained structures and morphologies depending on the process parameters and compare the data with SOA MEAs. The project may also investigate new active layers developed in laboratories.
- It is uncertain whether studies of fuel cell performance belong within the scope of this project. This team should include the impact of different manufacturing methods on the cost of the final product, including material yield impacts.
- The project scope could include a brief explanation of the long-term strategy and goals, especially on how the accomplishments and findings will eventually help achieve the cost targets.

Project #MT-008: Hydrogen Energy Systems as a Grid Management Tool

Mitch Ewan; Hawaii Natural Energy Institute

Brief Summary of Project:

The objectives of this project are to (1) support development of a regulatory structure for permitting and installation of hydrogen systems in Hawaii and (2) validate the performance, durability, and cost benefits of grid-integrated hydrogen systems. The validation entails three tasks: (1) dynamic operation of electrolyzers to mitigate the impacts of intermittent renewable energy, (2) demonstration of the potential for multiple revenue streams from ancillary services and hydrogen production, and (3) introduction of hydrogen fuel for shuttle buses operated by the County of Hawaii Mass Transit Agency and Hawaii Volcanoes National Park.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach has generated a large number of data and opportunities for additional work that should be addressed in future work plans. These future work plans should include advanced work on codes and standards, vehicle testing, infrastructure development, and the testing of utility products such as voltage control and frequency regulation.
- The team overcame past barriers that delayed the project and is poised to make excellent progress now and in the future. The grid ancillary services concept is very important to the integration framework of this project. The team's focus is very appropriate and inclusive—e.g., technical feasibility, validation of economics, and pioneering a regulatory structure.
- This is a good approach to evaluating the benefits of using electrolyzers to balance the grid load.
- The overall approach to the work is sound—modeling followed by testing. However, not many details were presented concerning how the work ahead is being planned, and it is therefore not possible to comment on the details of the approach that will be followed for the work ahead. The presentation did not reveal any of the key performance indicators (KPIs) that the project is targeting. In the absence of KPIs, it will be difficult to evaluate project progress. This should be remediated, and the project team should set clear technical and economic indicators.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Although there were some delays following the extensive modeling done in the earliest part of the project, the project is now ready to start operation. This represents a significant advancement toward achieving the project goals of validating performance, durability, and cost benefits of grid-integrated systems. During the last year, plant site preparations have been finalized, and the following seem to be in place: the hydrogen

electrolyzer, the hydrogen dispenser infrastructure, three buses re-converted to run on hydrogen, and three hydrogen transport trailers to carry 105 kilograms of hydrogen at 450 bars. A preliminary technoeconomic analysis of the project is still missing. This undermines the credibility of the project approach for potential replication activities in other locations and does not attract additional investors the project needs.
- The project has effectively shown that a hybrid battery/electrolyzer system can provide grid stability, while at the same time providing hydrogen for transportation applications on the island.
- Overall, this project meets the goals of DOE of how to best advance hydrogen infrastructure and market transformation.
- The project team has made excellent progress in this performance period, albeit part of it was trying to catch up from unanticipated delays incurred last year.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- All the relevant key entities in the State of Hawaii are involved, in addition to the federal partners, national laboratories, and industry partners.
- The list of sixteen organizations cooperating on this project is impressive.
- Collaboration and coordination with other institutions appear to be of high value. Additional collaboration with utilities is recommended.
- The project has excellent collaboration and coordination with others, as reflected in the project’s sufficient funding to complete the installations and to obtain the required permits. Still, last year’s project review noted the team lacked engagement with utilities. This still seems to be the case. As the project is now ready to start running additional exchanges with market actors to foster an expansion of grid services, the replication of the project elsewhere should be planned.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The successful completion and demonstration of this system will have implications for grid management across the country, as well as provide low-cost hydrogen for other projects.
- The project involves multiple hydrogen markets and applications that can deliver added value. This is a truly necessary ingredient for new energy systems.
- This project has high value as a template for future work and technology transformation at other locations.
- As stated in former reviews, the relevance and potential impact of this project is very significant. The project offers a sound example of the role that hydrogen technologies can have with grid balancing in an energy system with a high share of variable renewables, as well as a means to decarbonize the transport system. The project continues being of high relevance to the H2@Scale initiative. As operational data become available, the team should increase project visibility. In this regard, the project should disseminate the results to the scientific community and communicate the benefits of the project to the wider public. This can raise awareness and foster public acceptance of this type of project.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work of engaging with utilities for grid products is appropriate and would be of high value for technology transformation.
- The presenter provided an excellent summary of the proposed future activities. It was good that the slide included support for public outreach.
- Completing and testing systems is important, as is the public education aspect of this project once the volcano settles down and tourists return.

- The project is missing a clear plan for future activities. Instead, the team provided a set of individuals and activities during the presentation. It is not clear how far the project intends to go and how it will help to foster replication. Additionally, it is not clear how project success will be measured—this should be addressed.

Project strengths:

- The project has an excellent mix of local, federal, and state government collaboration and validation platforms (fuel cell buses, electrolyzer, potentially airport ground handling equipment, etc.). There is good emphasis on lessons learned and technology transfer. Utilities (e.g., Hawaii Electric Light Company) are interested. Enterprise Rent-a-Car and Kona Airport management are interested in collaborating through deploying fuel cell vehicles. Measures to address the corrosive environment (e.g., salt in seawater) and collaboration with Toyota Fuel Cells group were potential activities mentioned by the presenter.
- The project offers a sound example of the role that hydrogen technologies can have in grid balancing in an energy system with a high share of variable renewables as well as a means to decarbonize the transport system. The project fits very well with the objectives of H2@Scale, and there is great potential for replication. The project leader is dedicated and committed. This reinforces project continuity, although additional funding will be needed.
- The project demonstrated a good combination of grid stabilization and supplying hydrogen for shuttle buses. The project also provides a good opportunity to educate tourists in Hawaii.
- The data has been managed properly; however, as additional information and results are produced, additional provisions for management and dissemination of data will be needed.

Project weaknesses:

- The project could be more organized and focused on goals and pragmatic execution. Some project goals, including frequency regulation, appear to have been addressed with battery technology and without input from utility stakeholders. This objective is of high value and should be assessed for hydrogen fuel cell technology with utility involvement.
- There is a lack of engagement with the wider public and potential investors, as well as with utilities. This is key to demonstration of the market potential for multiple revenue streams, from ancillary service to grid balancing. Also, a technoeconomist analysis is still missing. It is unclear what the project KPIs will be; hence it is difficult to determine whether the project is achieving its objectives.
- The technoeconomic analysis capability is nearly completed; however, it will take time to get data that the capability can use.
- There is no specific data on the electrolyzer's ability to meet transient loads and stabilize grid frequency. The team includes only the statement that the electrolyzer was "close" to providing stability.

Recommendations for additions/deletions to project scope:

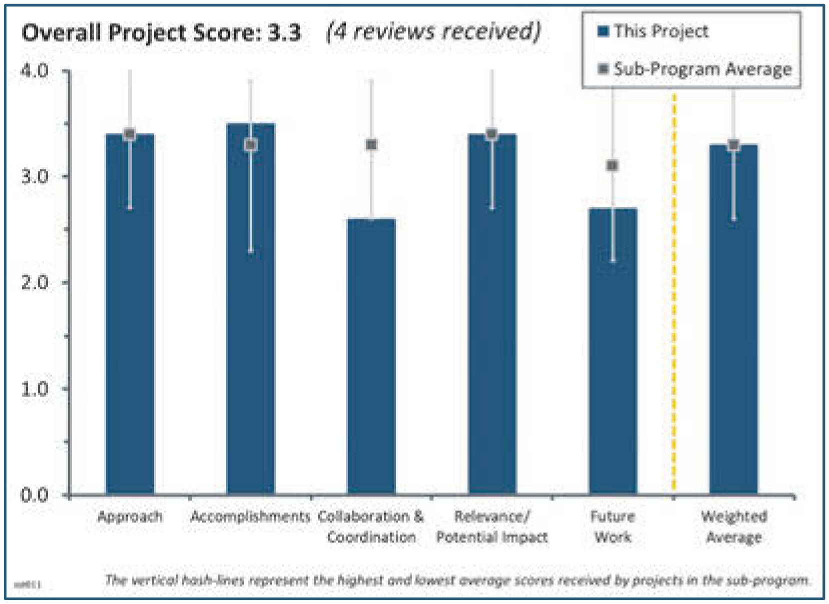
- The project's scope is appropriate. The team should establish both technical and economic project KPIs, develop a clear project plan for the work ahead, and plan for activities to foster replication. If relevant to the regional context, the team should investigate the role of hydrogen injection in the gas grid.
- The project team should continue work to assess grid products, including frequency regulation, voltage control, and energy storage, coupled with intermittent renewable generation with all costs and values. This work should be undertaken in concert with utility stakeholders.
- The project team should provide specific data on electrolyzer response time and any possible remedies to make it fast enough for frequency stabilization.

Project #MT-011: Fuel-Cell-Powered Airport Ground Support Equipment Deployment

Larry Pitts; Plug Power

Brief Summary of Project:

The objectives of this project are to develop fuel-cell-powered ground support equipment that (1) is cost-competitive and more energy-efficient, (2) is lower in carbon emissions, (3) reduces consumption of diesel, (4) decreases energy expenditures, and (5) validates the value proposition. This project will deploy 15 fuel-cell-powered units for two years at Memphis–Shelby County Airport. The fuel-cell-powered cargo tractors will be located in Memphis, Tennessee, where FedEx Express has a fleet of 1,383 cargo tractors to manage 270 flights per day.



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The overall project objectives were straightforward and obvious, so there was not much interpretation needed in developing a plan. When technical issues were encountered, the project team took decisive action to rectify them.
- The approach helps with understanding the operator interaction with the fuel cell through the use of real hardware compared to other technologies.
- This project had a good approach that dealt directly with the customer in real-life situations.
- This project has a very good approach with a nice demonstration.
- It would have been helpful if the presentation format had been followed.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The application is a good one; it is difficult to make the technology work in airport environments with all of the diesel and jet fuel emissions in air.
- The replacement of the fuel cell for the entire fleet in a short time was an outstanding achievement.
- The project team had good results on correcting failure modes, etc.
- The demonstration was run with a complete set of tractors and gathered enough data to do meaningful statistical analysis. It would be helpful to see some additional economic data supporting the total cost of ownership (TCO) compared to diesel (and battery) tractors. For example, it seems like the hydrogen storage/dispensing system is greatly oversized/expensive for the likely usage of this fleet, so it would be good to see some data and analysis on how the size was chosen or whether it could be optimized.

Question 3: Collaboration and coordination

This project was rated **2.6** for its collaboration and coordination with other institutions.

- The project team obviously collaborated well by achieving the installation of liquid hydrogen infrastructure and fleet of fuel cell tugs. It is not clear whether there is any collaboration with the airport on comparing operation of fuel cell tugs with operation of diesel tugs.
- This project was pretty much the application and adaptation of an existing commercial product to a new application, so it seems that the collaboration was pretty much limited to Plug Power and FedEx.
- The project appears to involve not technical collaboration but rather collaboration with users (drivers) and the company using the vehicles (FedEx).
- Given the effort to replace the fuel cells for the entire fleet, it must be assumed that a high level of collaboration was achieved, but it is an almost impossible task to provide a score. For that reason, a score of satisfactory was assigned because the exchange was accomplished and must have taken considerable collaboration and coordination.
- There was no collaboration identified because the review format was not followed and no collaborators were named, making it very difficult to provide a score.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This is a very strategic project. The success of this project opens up new market segments in the materials-handling space that has been an outstanding success for the fuel cell industry. The project opens up the opportunity to install hydrogen infrastructure at airports, which in turn opens up transportation market opportunities such as airport shuttle buses and rental car fleets.
- Emissions from ground equipment at airports are a very significant and difficult problem. It is very important to investigate the possible role that fuel cells could make in this application. Fuel cell technology may be the only zero-emissions technology that could meet the demands of this application.
- Obviously, this project is very relevant to the goal of getting hydrogen fuel cell vehicles into the real world.
- It is relevant to show the application of the commercial materials-handling solution to this specific application. However, no new ground was really broken by the project technically. A new industry/operator was introduced to the technology, which is always a good thing.

Question 5: Proposed future work

This project was rated **2.7** for its proposed future work.

- Dispersing the fleet of ground handling equipment to other airports provides the opportunity to introduce the technology to other potential users of ground service equipment (GSE) at very low technical and economic risk. The units have already been operated in an intense operational environment with a major player (FedEx) and therefore have the credibility that will make it easier for other airports and end users to make informed decisions.
- The vendor should work with the airport in comparing hydrogen fuel cell tugs with diesel tugs in terms of operating costs (fuel, operations and maintenance, etc.).
- It is not completely clear whether the 2018 end of this project was part of the original plan or if it is driven by FedEx's request that the hydrogen fueling site be relocated. The poster states, "Explore prospects for relocating the fleet to another location," so it does not necessarily seem that there is/was a clear plan in place.

Project strengths:

- The project team proved short-term satisfactory operation of GSE by a major company (FedEx) in an intense operational environment; met the technical objectives of the project; overcame a major technical problem with the original fuel cell that required the replacement of the whole fleet of fuel cells; and accomplished the Plug Power mission and did not quit, thus preserving the integrity and reputation of the DOE Hydrogen and Fuel Cells Program. If the project team had quit, it would have been a public relations disaster for the fuel cell industry. Plug Power has earned thanks.
- The demonstration of the unique zero-emission, rapid-fueling, long-range, consistent power output performance characteristics in this ground support equipment application is very important. The project started off with some failures, but the project team worked well through those to demonstrate well the technology in this important application.
- The project used real demonstration hardware to expand the applications in which fuel cell systems may enjoy the commercial success currently seen by forklift materials-handling systems.
- This project is an excellent, real-world project evaluation and comparison with existing technology.

Project weaknesses:

- There were a number of equipment-/performance-related problems initially, which may have made the FedEx operators reluctant to fully use the equipment. There was not a product validation plan/process described in the poster, so that may have been a missing element. Also, the project had a very short duration, and it is unclear whether it ended sooner than planned. As a result of these two things, the fidelity of the data as a tool for making investment/TCO decisions for the cargo tug application is unclear.
- The project team did not follow the Annual Merit Review report format, thus making it difficult to assign some scores. While this did not have an effect on the project outcome, it has hurt the overall ability to provide a comprehensive review score. This may not matter.
- The project needs to focus on operational cost comparison between hydrogen fuel cells and diesel tugs.

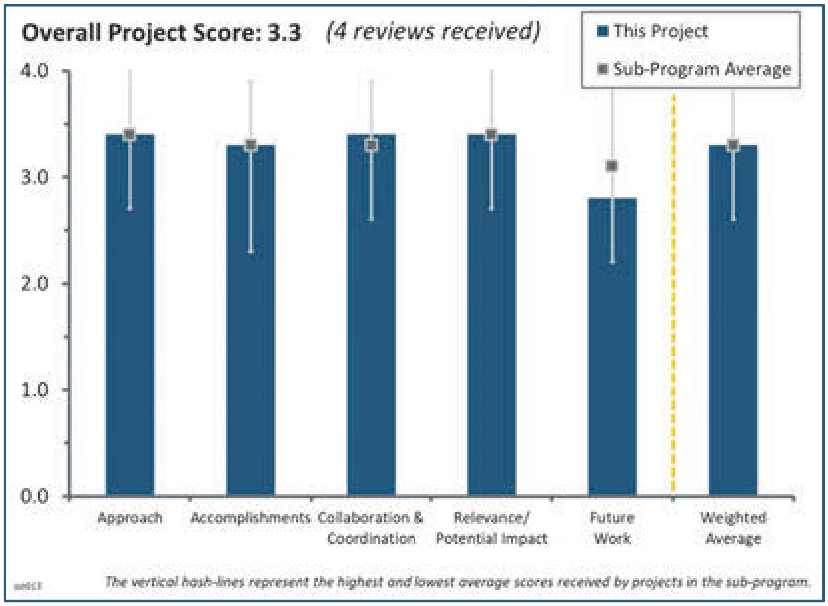
Recommendations for additions/deletions to project scope:

- The team should deploy GSE units to other airports to spread the success of this technology and open up the market.
- The project team should add a TCO analysis and comparison to incumbent technologies and add a validation plan to ensure that the equipment is reasonably reliable from the outset.
- The team should add a task for compart hydrogen and diesel fuel costs and operation and maintenance costs.

Project #MT-013: Maritime Fuel Cell Generator Project

Lennie Klebanoff; Sandia National Laboratories

Brief Summary of Project:



The overall objectives of this project are to (1) lower the technology risk of future maritime fuel cell deployments by providing performance data on hydrogen polymer electrolyte membrane fuel cell technology in this environment, (2) lower the investment risk by providing a validated business case assessment for this and future potential projects, (3) enable easier permitting and acceptance of hydrogen fuel cell technology in maritime applications by assisting the U.S. Coast Guard and the American Bureau of Shipping with developing hydrogen and fuel cell codes and standards, (4) act as a stepping stone for more widespread shipboard fuel cell auxiliary power unit deployments, and (5) reduce port emissions with this and future deployments.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project approach is very sound, including upgrading the fuel cell, main inverter, and operator interface and analysis of the optimum fueling scenario for the port. It is important for an operator to know whether the system is functioning as designed. Reducing startup time and enabling operation in cold weather are also good.
- Building and testing full-scale hardware to demonstrate the validity of the system and giving prospective users something to see and touch are good approaches. The rapid cycle of feature/design improvements and retrofits based on learning from the first deployment is also a good approach. It is not clear how the approach for supplying hydrogen fuel was planned. It seems like the approach that was used (tube trailers) ended up being very expensive and did not demonstrate the cost-effectiveness of the system.
- The approach appears appropriate and aligned to provide meaningful feedback for the U.S. Department of Energy and the industry.
- The oral presentation covered a certain amount of bouncing around and included a thorough discussion of the relocation from Hawaii to Massachusetts but very little discussion on the relocation from Massachusetts. There may have been some excellent work in Massachusetts. The project team may have overcome or will overcome most barriers but appears utterly stymied by one barrier: location. The location problem may be especially concerning, as the project is scheduled to end this December; and the project has experience in Hawaii and a plan for and recent work in Massachusetts, but the project needs a home somewhere.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Project progress made included resolving technical issues identified in 2017, such as excessive downtime and the inverter's failure to meet operating requirements. In addition, enabling operation in colder weather is a very good accomplishment.
- The retrofit and testing of the unit based on learnings from the Hawaii deployment were successful. In terms of DOE goals, the project clearly demonstrates the ability to power refrigerated containers with a clean, quiet power source. However, it was unclear what the original plan for the second deployment was because, unfortunately, the arrangement with Massport could not be completed.
- Despite much excellent work and recognizing that the team made "outstanding progress toward project objectives," as documented by the extensive work performed in the written and oral presentations, the down-check comes because "there are weaknesses (a very specific weakness, location) that need to be addressed to improve the rate of progress...to overcoming barriers."
- This project contains good accomplishments and progress. Noteworthy is the work done by Hydrogenics to learn from the deployment activities in Hawaii and make improvements.

Question 3: Collaboration and coordination

This project was rated **3.0** for its collaboration and coordination with other institutions.

- There is outstanding, close, and appropriate collaboration among the partners. Whatever the reason for Massport's and Sandia National Laboratories' (SNL's) not reaching an agreement, that failure does not affect the recognized close collaboration otherwise present.
- The project contains great collaborations. Despite some setbacks, the project team is identifying great opportunities for new partnerships.
- Collaboration and coordination among the existing partners is very good, but the uncertainty associated with finding a port partner is still a factor.
- The collaboration between the project partners was good. However, the relationships with the organizations at the deployment sites have not gone well, so the unit has been "down" for six months while the effort is underway to find a deployment site. It is unfortunate that this could not have been done in parallel with the upgrade/test timing.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- It is important to show that fuel cells and hydrogen can compete in stationary applications to maintain momentum for the Hydrogen and Fuel Cells Program (the Program). This project, if successful, will contribute to this outcome. If the economics are not optimal, the benefits of gaining experience and engaging technology providers, regulators, and a port authority are still valuable.
- Despite the failure to secure an agreement with Massport and the lack of a location for a project with six months before its end date, the project nonetheless aligns very well with the Program as well as specific research and development goals. If the ability to complete the project or even the ability to have a location were part of the definition for relevance and/or impact, the grade for this section would be quite a bit different.
- The project has good relevance and impact and should continue to be funded/supported by DOE.
- It is very valuable to have a real, full-scale hardware demonstration. However, this particular project continues to have problems because the plan for deployment and responding to problems was not robust enough, so there is a concern that the reputation of fuel cells in this application suffered as a result.

Question 5: Proposed future work

This project was rated **2.1** for its proposed future work.

- The proposed future activities appear appropriate and beneficial.
- At this stage, owing to the particular circumstances for the project, a number of uncertainties may have an impact on future work. Therefore, the slide on future work tends to be less specific than the other slides. It would be good to document "lessons learned" for the benefit of the Program and its partners and contractors. The presenter said that the project is making progress in exploring the possibility of other host sites.
- The plan for future work is to try to find another deployment site. Hopefully, this will be successful, but it does not seem certain based on the problems with Massport. It is unclear whether the project team analyzed and understood the differences between the Hawaii deployment (what enabled it) and Massport. It looks like some additional work was done to improve the fueling plan at Massport, but it was still very expensive. It is unclear whether other alternatives were considered.
- The grade assigned (2.0) is a compromise between various considerations. On the plus side, the project team has built on past progress and is working to overcome barriers. However, the project team did not provide an indication that they can overcome the immediate weaknesses facing the team and complete the project by December. Further, the team was all but silent on the likelihood of overcoming the barriers. A better discussion of the immediate challenges ahead might have improved the grade.

Project strengths:

- The project has good direction, project leadership, and partners. The project is wisely building on previous learning to avoid future setbacks and delays. The work identifying new partners is well-thought-out and appears beneficial.
- The demonstration hardware was built and deployed, and lessons learned from the deployment were quickly incorporated into design changes/upgrades, which were implemented and tested.
- This project has very good collaboration and cost sharing among partners, industry, and other federal agencies.
- The greatest strength of this project is that the project focuses on real-world logistical challenges.

Project weaknesses:

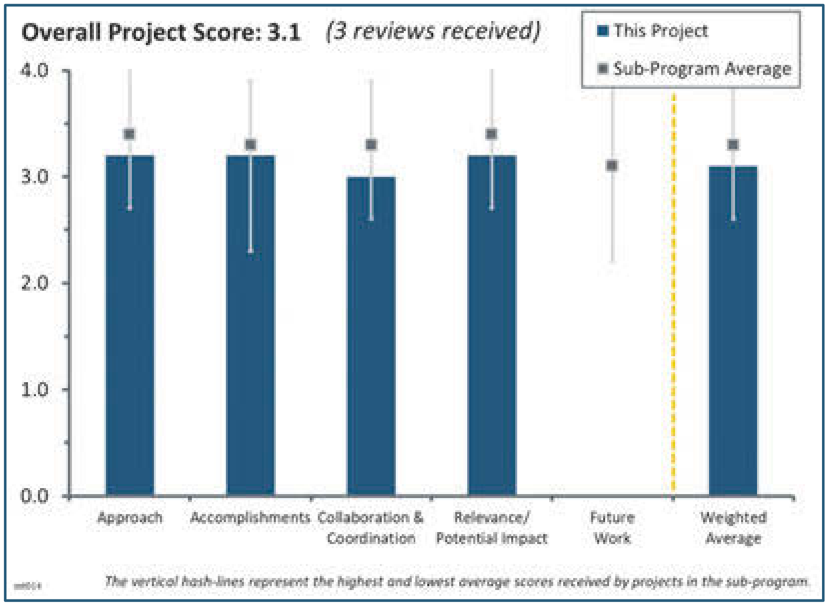
- The second deployment did not happen, and now there is a delay trying to find another opportunity. The issue of high fuel/operating costs was not really resolved, and it is not clear what alternatives were examined or what analysis of possible pathways was done.
- The double relocation, first from Hawaii and then from Massport, wastes time and resources that could be used for other aspects of the project.
- It would be good to develop a plan to secure lower-cost hydrogen supplies over a number of years.
- Keeping the momentum and project moving forward could be a challenge if funding issues arise.

Recommendations for additions/deletions to project scope:

- An analysis of operating cost is needed to be competitive with incumbent technology, and then an analysis of multiple pathways for providing hydrogen should be looked at to determine whether it is possible to become cost-competitive. It is unclear what delivered cost/kilogram for the hydrogen is required for the economics to work.
- Having to move from Hawaii might have been a good point to end the project. Most people would have understood that forces beyond SNL's control forced the abrupt end. SNL should take advantage of the Massport fallout to end the project and complete the report. This scenario is not ideal and may even be distasteful, but ending the project now would avoid future occurrences of the problems that caused the two previous relocations and avoid what could be a very sloppy end.

Project #MT-014: Demonstration of Fuel Cell Auxiliary Power Unit to Power Truck Refrigeration Units in Refrigerated Trucks

Kriston Brooks; Pacific Northwest National Laboratory



Brief Summary of Project:

The purpose of this project is to demonstrate the viability of fuel-cell-based transport refrigeration units (TRUs) for refrigerated Class 8 trucks using demonstrations and business case development. Two fuel cell systems will be developed and deployed in commercial operations. Investigators will assess system performance and analyze market viability.

Question 1: Approach to performing the work

This project was rated **3.2** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This project was thoroughly planned and provided two possible solutions and trade-off opportunities.
- The project would have benefited from a more rigorous assessment of user adoption criteria and how the criteria would be assessed against the proposed designs. The approach description talked about the "voice of the customer," but this appeared to be a single-criterion assessment of net present value (NPV). A more comprehensive approach could have considered other parameters, such as monetized impact on load-carrying capacity, and could have also looked at the cost to achieve zero emissions versus NPV comparison to diesel. The NPV results between the two teams could not be compared because of a lack of common assumptions (e.g., one team assumed a greenhouse gas [GHG] credit value, and one did not). Common technical and economic specifications would have improved the value and ability of the project to interpret the findings of two separate demonstration teams.
- The demonstration itself was good, but the justification and analyses that were accomplished with it were not too compelling. The team should have focused upon the very significant and important environmental benefits that the technology could produce, with regard to GHG emissions and especially to criteria pollutant emissions and air quality; these are the main reasons to pursue such a fuel-cell-powered auxiliary power unit (APU).

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project was well executed and provided an in-depth analysis of the technical and economic aspects of this potential fuel cell application. It is necessary to have a more challenging market environment that makes the economics work, such as military forward operating bases, where diesel can cost over $200 per gallon delivered and where delivering fuel can cost the lives of our servicemembers in a combat environment. It is also necessary to reduce the capital cost of the equipment and investigate design changes.
- It is good to demonstrate that this technology works to support TRUs. There should be an emphasis on the environmental benefits, which are especially challenging to achieve in ports, where these types of loads and generators are concentrated.

- The work of the two project teams was terminated prior to the intended field demonstration. For this reason, in-service cost, reliability, and customer experience objectives could not be addressed. The design and business case tasks met the stated requirements.

Question 3: Collaboration and coordination

This project was rated **3.0** for its collaboration and coordination with other institutions.

- Several companies with competing technologies and business cases were involved, which supported a thorough evaluation of the technical solutions.
- The project team put together a strong core team of fuel cell manufacturers who were active in warehouse and goods-movement applications and were the two leading providers of APUs. The team also secured one demonstration host (the other dropped out). The project might have proceeded to full demonstration if gate criteria had been clearly defined up front. (Presumably, this was not done, but it was not clear, for example, what assumptions on hydrogen and diesel prices drove the no-go decisions.) Participation of an air district might have provided additional pull to get the project through to the demonstration phase.
- There does not appear to be any significant technical collaboration on the advancement of the technology itself but rather reasonable collaboration with the end user.

Question 4: Relevance/potential impact

This project was rated **3.2** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project provides a technical and economic baseline departure point for future efforts and new solutions. The market is not quite ready, but the concept is conceivable enough that changes in the situation could make it economically viable going forward.
- The project team addressed an important niche application with the potential to support early market entry for fuel cells. Valuation of emissions benefits and possibly forecasting of improved cost and weight in next-generation solutions might have created a stronger case to move forward to demonstration.
- The project could have been much more impactful if it had focused on the technology’s environmental benefits instead of the economic benefits. The team should be working with local air quality management districts in affected areas (e.g., Houston, New York/New Jersey, Los Angeles/Long Beach) to incentivize and support, if not mandate, the use of this technology.

Question 5: Proposed future work

This project was not given a rating for its proposed future work.

- The project has been completed.

Project strengths:

- The project’s strengths include a good technical approach and execution, as well as a good analysis of the business case and viability of the technical solutions. There is good exposure by industry of the potential of a hydrogen solution that could come into play if anti-idling policies also come into play. The team provided a good baseline upon which to base new technical solutions.
- The project addressed a potentially important application that ties to emissions reductions in goods movement. The team did well in securing strong fuel cell and APU partners.
- The demonstration of this technology for use in APU applications is important. The project appeared to succeed in doing this for the first time.

Project weaknesses:

- There are no weaknesses under the control of the project.
- The lack of emphasis on environmental benefits was the most significant weakness. The economic analyses were not too compelling, and the poster presentation itself was poor. The principal investigator was available at the poster but was difficult to engage in that setting because of the focus on one questioner at a time.
- Some areas that could have been improved include the gate criteria, which were not clearly defined, and the unpresented technoeconomic assumptions (such as discount rate); it appears that the teams did not use common assumptions.

Recommendations for additions/deletions to project scope:

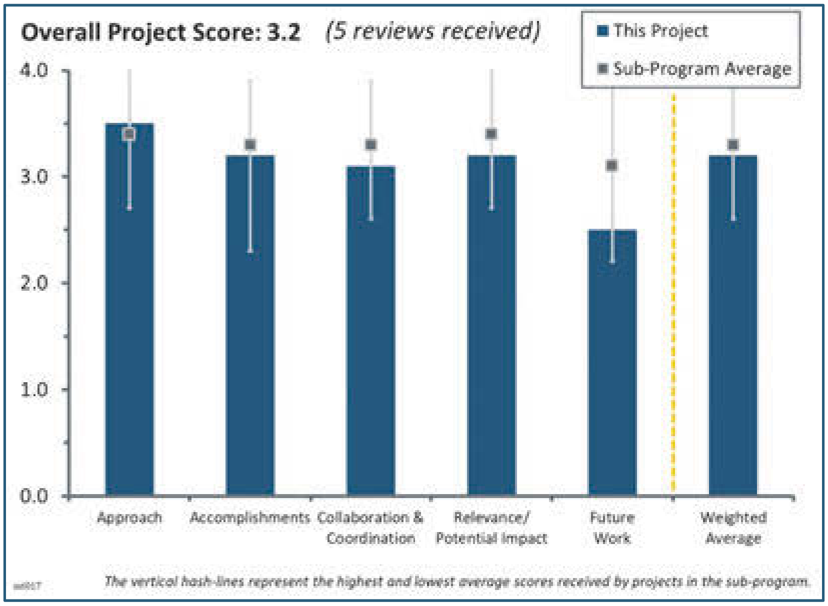
- The project is complete, so recommendations are not applicable.

Project #MT-017: FedEx Express Hydrogen Fuel Cell Extended-Range Battery Electric Vehicles

Phillip Galbach; FedEx Express

Brief Summary of Project:

This project will demonstrate hydrogen and fuel cell technologies in real-world environments. Fuel cells are being integrated into 20 battery electric pickup and delivery vehicles. Those trucks will operate 10-hour shifts 260 days annually, amounting to at least 5,000 hours per truck for a total of 100,000 hours over 1.92 years. The project is expected to reduce diesel consumption by 100,000 gallons and prevent 270 metric tons of carbon dioxide.



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project objectives are well identified on the technical, environmental, and economic levels. From a technical point of view, the project is already testing the first prototype to validate its design and gathering data on its performance. The fact that a clear control strategy has been put in place will allow for further optimization of the fuel cell system and validation of its design. From an environmental point of view, the benefits that can be achieved are also specified, even though the sources from which the hydrogen for the project will be produced are not explained. In terms of barriers, the principal investigator (PI) has clearly stated that, besides the validation of the prototype, one key obstacle is to overcome concerns safety. With a greater number of hydrogen vehicles, new safety issues that need to be considered will emerge.
- The overall approach toward achieving the project objectives is sound, as demonstrated by the development of the powertrain. The test of the first prototype, before deciding whether to deploy a larger fleet of vehicles, followed by integration, was a good approach. The project's go/no-go point is the right approach for these types of projects. The role of each of the partners in the project is clear.
- There is an excellent partnership with FedEx, with the company's dominance in the truck delivery business. Comparing fuel cell trucks with conventional trucks was also a good approach.
- The team is running a little over budget and has suffered nasty personnel turnover. The team has some real challenges. At this point, this team has a real chance of failing miserably, but if successful, the project could well have an impact on the delivery vehicle sector in much the same way the Defense Logistics Agency (DLA) (and later the U.S. Department of Energy) transformed the use of fuel cells in forklifts. The team's approach is commended.
- The lack of continuity of project personnel is a concern for ensuring project success.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The test and validation of the first vehicle and powertrain requirements have been finalized. Following this, the first prototype has been up and running since January 2018. A remote data collection system is in place

that sends data for analysis to the fuel cell provider, Plug Power. The month of February saw little data, as the vehicle was down most of the time. This is normal following early (and especially winter) operation, and it is welcome to see that few issues were observed in the posterior months. The PI did not present any data analysis, as it was not ready.
- At the end of Budget Period 1 (BP1), the project is on schedule despite several difficulties during the first few months. It appears that a set of performance goals for the vehicle was not established before the beginning of the validation phase. However, the data-gathering techniques put in place by the consortium (data transmitted via mobile connection to a central database) will certainly help to gain a deeper understanding of the performance that can be achieved by this hybrid powertrain and contribute to the achievement of the DOE's overall goals.
- The project team appears to have struggled with schedule milestones, but the project now seems to be on schedule. In BP1, the team was slightly over budget, but it is close enough that the team should be able to overcome this currently minor discrepancy.
- The project team is off to a good start but must deploy the full 19 fuel cell trucks to provide a true comparison with existing technology.
- The DOE project objectives provided on slide 3 indicate "20 parcel delivery trucks will operate on shift 260 days annually for approximately 10 hours per day." Given that one vehicle has yet to yield substantial field demonstration results, it appears unlikely that the project can complete its activities by the October 2020 project end date.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- The interaction among partners seems appropriate, and the role of each within the project is well defined and in line with their expertise. Cooperation with other projects carrying similar activities in the same domain (range extender) was not mentioned. The cooperation with relevant agencies (i.e., the safety panel) is foreseen in the plan and appears appropriate.
- Collaboration and coordination among partners have been excellent, and a reflection of this is that the first prototype is already in operation. This demonstrates a good collaboration between the fuel cell supplier, Plug Power, and the system integrator and end user, FedEx.
- Partner organizations all seem to have well-defined roles and appear to each be meeting their individual responsibilities.
- There is good collaboration with commercial partners and with the National Renewable Energy Laboratory.
- The vehicle maintenance partner is not well defined.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is well in line with the market transformation objectives of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, as its goal is indeed to validate early business cases and validate technologies in real-world conditions. Furthermore, it has also been highlighted that the goal of the reduction of pollutants and greenhouse gas emissions is of common interest to the intended user of the new vehicle (FedEx) and the DOE Office of Energy Efficiency and Renewable Energy. The collection of data throughout the vehicle's use will provide useful insights and allow for progress toward these goals.
- FedEx seems to have a clear plan and strong commitment to fleet electrification. Should this project be successful (with cost and reliability at acceptable levels), the impact would be significant and could potentially be extended to other vehicle operators.
- This project could change the delivery vehicle sector in much the same way that the DLA investment in fuel cell forklifts changed that particular industry.

- If this project can encourage FedEx to convert its huge fleet into one that operates on fuel cells, it would be a major accomplishment for the hydrogen fuel cell establishment.
- The project looks to be beneficial, but given the problems with demonstration activities of the first unit, it is unclear that there will be substantial relevance/impact.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- This is a good plan. If FedEx decides to proceed, it will be a major accomplishment since the team must fund the next phase and then await DOE reimbursement; hence, a FedEx commitment to front money for this project would be a major achievement.
- The proposed future work is dependent on a go/no-go decision date that is planned for October. It seems likely that the team's October decision will be correct.
- The continuation of the project will be subject to FedEx's decision, as part of the go/no-go point. This will depend mainly on (1) demonstrating acceptable levels of reliability for the first vehicle prototype, (2) securing adequate levels of maintenance for the larger fleet of 20 vehicles to be deployed, and (3) putting together a convincing business case to FedEx management to finance up front the deployment of the 20-vehicle fleet. The project consortium is well aware of this. As presented, the prototype vehicle will be tested until September 2018. Following this, data will be analyzed, and the go/no-go decision will take place at the end of October 2018. This timing is very challenging, and it is recommended that the project extend the testing and data collection exercise to one year—and therefore postpone the go/no-go decision until the first quarter (Q1) of 2019.
- The logic of the work for the remaining period, in theory, is clear: if the first prototype reaches satisfactory results, the consortium will continue with building the other prototypes and start gathering a large number of data that will allow the team to have a better idea of the performance of this type of powertrain (fuel cell and hydrogen range extender) for the intended use. At the same time, the PI clearly stated that many factors will have to be taken into consideration for the go/no-go decision, some of which might prove difficult to overcome. The team's ability to ensure standard safety compliance for the next phase (linked to the management of several hydrogen vehicles), in particular, was flagged as a serious challenge. As a consequence, scarce data were provided for the actual implementation of the project during BP2, as there seemed to be some skepticism about the project team's ability to continue.
- The project does not appear to have enough time remaining to accomplish the goal for demonstrating operation of 20 units. In addition, there are potential safety issues that are yet to be addressed, which could require redesign and greater costs.

Project strengths:

- The involvement of FedEx offers an interesting exploitation potential. If the fleet of 20 vehicles proves to meet the company's needs, the project team would have the capability of rapidly upscaling this hydrogen-based solution. The team's method of gathering data on the operational performance of the vehicle in a centralized database is also very good.
- FedEx appears to be a good partner that could enable beneficial results/learnings if the project objectives are met.
- The strength of this project is in the leverage opportunity the project can create for delivery vehicles. If DOE would like to replicate the success enjoyed with fuel cell forklifts, additional resources might be necessary.
- This is clearly a market-oriented project driven by strong end-user demand. There is significant replication potential within FedEx and also potentially in other fleet operators.
- This project has an excellent real-world partner to evaluate fuel cell hybrid delivery trunks in real-world applications.

Project weaknesses:

- Personnel changes seem to have plagued this project, but it appears to be moving ahead in any case.
- This is not a weakness in itself, but it is unfortunate that the total cost of ownership analysis was not ready to be presented during the project presentation.
- There are many project weaknesses, including a massive turnover of personnel. Another problem appears to be the miserable performance reliability of the fuel cell systems. Time and budget management may be a challenge that will not be overcome. Finally, the many challenges facing the team may overwhelm the project leadership and the supporters so that the project falls apart when it does not need to.
- The project is utilizing a storage tank location/configuration that exposes piping and valves to anticipated impact zones. This did not appear to be a safe configuration.
- A weakness is the uncertainty concerning the continuation of the project.

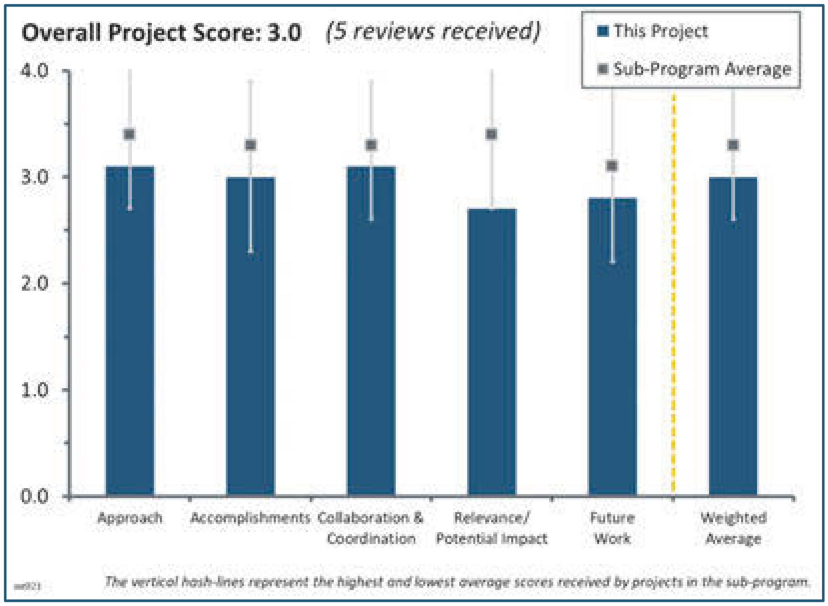
Recommendations for additions/deletions to project scope:

- As presented, the prototype vehicle will be tested until September 2018. Following this, data will be analyzed, and the go/no-go decision will take place at the end of October 2018. This timing is very challenging, and it is recommended that the project extend the testing and data collection exercise to one year—and therefore postpone the go/no-go decision until Q1 2019.
- Other safety issues identified during the submittal of the safety plan should be addressed for the design prior to the construction of additional vehicles.
- If true “zero emissions” is a goal as stated, then at some point the project might consider photovoltaic-generated hydrogen (perhaps in California) to run these trucks.
- DOE may want to consider a more active management role. The problems facing the team members may overwhelm their ability to complete the project.

Project #MT-021: Northeast Demonstration and Deployment of FCRx200

Abas Goodarzi; US Hybrid

Brief Summary of Project:



The project's objectives are to (1) design, develop, test, and demonstrate one fuel cell range-extended plug-in hybrid utility vehicle (FCRx200) at a commercial operator's site; (2) given the success of the initial prototype, receive approval to proceed with fleet development to deploy and operate a minimum of 20 FCRx200s for at least 5,000 hours or 30 months per vehicle, whichever occurs first, at the commercial operator's site; and (3) conduct an economic assessment, a payback analysis, a life-cycle cost analysis, an incremental capital cost per unit analysis, a fuel savings analysis, and a payback time analysis (concerning the use of hydrogen-fueled fuel cell range extenders in commercial fleets), as well as comments from the operator detailing the experience during operation. The economic assessment will be facilitated using data collected and submitted to the National Renewable Energy Laboratory on a quarterly basis. Upon project completion, the team will be able to make recommendations on the marketability of the FCRx200 vehicle.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The presenter made the challenges and nuances of the project crystal clear; this presentation might have been one of the best of the U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program (Program) Annual Merit Review (AMR) presentations. Especially noteworthy was the detailed presentation of the team's approach, as well as the modeling and system analysis.
- The approach of the project, overall, is well designed. Following the development stage, the team will test and demonstrate one fuel cell range-extended plug-in hybrid utility vehicle; should the initial prototype be successful, it is expected to be deployed in a fleet of 20 vehicles. Following the 2017 AMR, it is welcome to see that an initial economical assessment has already been undertaken at this stage—originally, this was slated to be done only at the end of the project, which expert reviewers considered too late. The economical assessment presented by the principal investigator (PI) contains a number of underlying assumptions that were not presented in detail. It was therefore not possible to assess the robustness during the project presentation—also because it was not yet time to discuss these aspects. It would have been useful, for instance, to get further insight on the fuel cell system cost assumptions, as the current figures show $14,000 for a 10 kW system, which seems very low. However, to fully assess this, it would be necessary to understand the technology the fuel cells used, whether they were polymer electrolyte membrane fuel cells or solid oxide fuel cells. It was not possible to get the details on this.
- The objectives of the project are well described and well enshrined in the philosophy of a market transformation project. Much of the focus is on the optimal integration of a fuel cell system in a battery electric vehicle (BEV) with the scope of enlarging the application of the vehicle and making it more marketable. The main barriers considered by this project are of a technical and economic nature. From a technical point of view, the key achievement obtained to date is the design and engineering of the system to

fit into a pre-existing chassis. While it is well understood that the scope of a market transformation project is not to improve the performance of individual technical components, the aspect of system performance did not appear to be sufficiently considered. In other words, it is not clear how much attention was put into optimizing the system (in terms of range, durability, efficiency, etc.) during the design optimization phase to get the best performance possible. Cost and customer satisfaction are the key, if not only, parameters considered.

- The approach seems reasonable, although the exact objectives seem rather vague.
- The presentation did not adequately demonstrate why these activities are good for the Program or the broader fuel cell community.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team's measurement of its technical achievements was noted often during the review. Among the project advancements, the team recognized when it was necessary to increase the fuel cell from 5 kW to 10 kW, completed freeze testing of the stack, and seem to have made sound design adjustments.
- The project concept is well aligned with DOE goals in terms of market transformation. If successful, this project will enable original equipment manufacturers (OEMs) to find a commercial application for the vehicle in which the fuel cell range extender system will be integrated. The project implementation is following its original path. Whether the project will achieve its goals, however, is hard to judge at this stage. In fact, most of the measurable performance indicators will be made available at the end of the project. Select technical data were presented; however, these were not compared to initial technical goals, making it difficult to understand whether the progress was in line with the plan.
- The work to date has been focused on the design and development of first prototype powertrain. This work is ongoing but close to being finalized. The information provided does not make it easy to understand the key performance indicators against which the fuel cell has been designed; therefore, it is not possible to fully understand whether the design specifications are in line with specific DOE targets. For instance, no information was given on the durability and lifetime of the fuel cell. The PI seems to be well aware that the end product should meet OEM requirements; nevertheless, it is necessary to trust that the PI will meet performance targets. For the go/no-go point, it will be necessary to ask for more details on the performance targets achieved, as well as those remaining on the project timeline. In this regard, a Gantt chart or a similar graphic illustrating key progress and milestones that have yet to be achieved, as well as depicting planned tasks, would help.
- While the project is making some progress, it is not clear that the results will be helpful for DOE goals.
- It is too early to tell how the project team is doing.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The PI declared that the team made efforts to reach out to similar projects (dealing with range extenders) but did not succeed in making contact; these efforts should continue in the next budget period. The coordination of the partners involved in this specific project is appropriate. The consortium is well conceived, and each partner has specific expertise that fits well with the overall purpose of the project.
- There are active roles for each of the collaborators. The team appears complete, and each collaborator is fully on board.
- The project seems to be well managed, and collaboration among consortium partners has been positive—especially between the powertrain provider and the OEM. Should the first prototype result be successful, the project team should try to engage with other potential end users to foster replication during the demonstration phase. It is suggested that a plan on how this can be achieved be developed before the demonstration phase starts. In this regard, the PI has mentioned that the team has contacted a large number of potential end users, but no further details were provided. It is unclear whether the powertrain supplier

fully owns the intellectual property rights of the powertrain to be integrated, and hence it is difficult to assess how relevant it would be to also target other OEMs at a later stage.
- The project appears to have a good team for the anticipated activities. However, it is not clear that all project partners (Nissan, for example) are engaged or committed to the project's success.
- This project does not seem to address the overall market projection for utility vans. It is unclear how many there are in the United States and whether successful demonstration of these vans could apply to other van markets.

Question 4: Relevance/potential impact

This project was rated **2.7** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Overall, the project is well aligned with the Program's goals and objectives; should it be successful, the project could contribute to opening up new markets for fuel cell applications in the automotive sector. However, how the project intends to build volumes beyond the 20-vehicle fleet remains unclear. To clarify, the perspective of the OEM should be represented for the next project review.
- If successful, the project will indeed help to advance the goals of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan, as it will allow the final user, involved in the project, to make use of a new hybrid powertrain. At the same time, from the materials provided, it was hard to understand two important elements: it was unclear which innovations the project would generate (it appears that design optimization will not be disclosed, as it is deemed commercially sensitive), and therefore, it is unclear who else, besides the partners involved in the project, will be able to benefit from this activity.
- The project team's work and success may have an outsized impact on both the automotive industry and the fuel cell industry. The bigger problem is that while this team is performing outstanding work, the beneficiaries of this work may be overseas companies and other nations, rather the United States and domestic companies. This is due in large part to the funding of the national laboratories, rather than the U.S. industry, coupled with the relative inactivity among domestic OEMs.
- It is unclear how this project, if successful, would affect the total van market.
- Given the presenter's focus (in enabling a bill of materials), it is unclear whether the project is aimed at meeting the FCTO goals and objectives.

Question 5: Proposed future work

This project was rated **2.8** for its proposed future work.

- The team proposes additional work in a wide variety of areas (i.e., fueling interface, vehicle cooling, structure analysis, driver interface and telematics, balance of plant, sensors and safety, performance validation, and demonstration) that are all crucial to success. These areas include problems of which any regular user of fuel cell electric vehicles is well aware, and the team knows that a resolution is necessary.
- The proposed future work seems like a reasonable plan to get these utility vans on the road and under testing.
- On a general level, it is clear what the remaining work is intended to be. However, no details on the remaining project activities were presented, especially on the "how." Next year, a Gantt chart should be presented showing completed progress but, more importantly, showing uncompleted tasks and milestones to be achieved. The most important immediate milestones are (1) the point in time when the first prototype vehicle is ready to start operation, followed by (2) the first-year results to be obtained before deciding whether the wider 20-vehicle fleet is to be deployed.
- The main blocks of the remaining work are laid down in a clear manner; however, scarce details were shared on the next steps. It is also not clear which elements will be considered for the go/no-go decision.
- The lack of a safety plan or hazards analysis suggests that the project is not well prepared for future work.

Project strengths:

- The project has a pragmatic approach and, if successful, will allow the final user to commercialize a pure BEV that, for the time being, has no commercial application. It will, therefore, help to make the case for the use of fuel cells and hydrogen technologies in transport. Furthermore, the strong focus on the customer needs of the project will also allow the team to show the financial sustainability of the hybrid solution proposed.
- This is a market-oriented project with apparently committed partners—both the powertrain supplier and the OEM. The project has clear potential to open up new markets, in particular, for the retrofitting of BEVs with fuel cells to extend the range.
- There are many project strengths. The presentation looks at many challenges and appears to have answers, or at least a plan to pursue for all. Throughout the presentation, the team lists many interesting observations and potential solutions.
- The project contains a good OEM and national laboratory development team.
- No specific project strengths were identified by this reviewer.

Project weaknesses:

- The innovation potential of the project is not entirely clear. Much effort will be put into designing the system and integrating it into an existing powertrain. It appears, however, that large parts of this effort will remain unknown outside the consortium involved in the project (due to commercial sensitivity). Much of the effort, then, seems to be oriented to the customer satisfaction of the final user involved in the project; therefore, the project is targeting a very specific vehicle for a specific use, defined by one final user. Therefore, it is not clear at this stage that the fuel cell and hydrogen industry as a whole will be able to benefit from any of the findings of this project.
- The project appears to be moving forward, despite having no commitment to safety planning or a safety plan and no hazards analysis (waiting until the design is complete is inappropriate and puts the project at risk both financially and in terms of ensuring safety). Additionally, since fuel tanks are to be located in the front of the vehicle, the project team should be transparent and thorough on the basis of the safety of tanks in credible crash scenarios.
- The project's technical KPIs remain unknown and should be provided to enable assessment of the accomplishment of specific DOE targets. It is unclear how the project intends to build volumes beyond the 20-vehicle fleet. To clarify, the perspective of the OEM should be represented at the next project review.
- The impact of this project is its weakness because, even if successful, it is not clear if this has a significant market share.

Recommendations for additions/deletions to project scope:

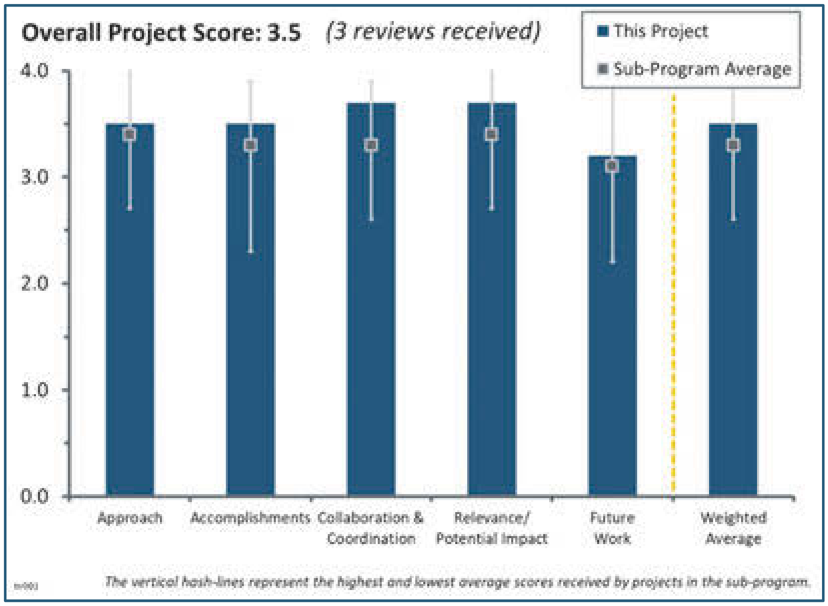
- No recommendations are offered; this was a very good presentation.
- A set of project KPIs seems to be missing—this will make it difficult to objectively asses the go/no-go point in the project. Technical details of the project remain unknown. A detailed project Gantt chart should be developed and presented. The perspective of the OEM should be better represented and conveyed in future presentations.
- It is recommended that the project put greater emphasis on technical achievements that go beyond the specific case assessed in the project (i.e., producing public deliverables exploitable by other players). It is also suggested that the project clarify the technical goals to be achieved and establish a clear dissemination and exploitation strategy.
- The overall value of continuing this project is questionable, given the lack of focus on DOE goals and objectives and a change in direction of the FCTO focus (early research and development).
- The protect team should analyze the fraction of the U.S. vehicle market that would be affected by the successful development of this fuel cell hybrid utility van.

Project #TV-001: Fuel Cell Electric Vehicle Evaluation

Jennifer Kurtz; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to validate hydrogen-powered fuel cell electric vehicles (FCEVs) in real-world settings and to identify the current status and evolution of the technology. The analysis objectively assesses progress toward targets and market needs defined by the U.S. Department of Energy and stakeholders, provides feedback to hydrogen research and development, and publishes results for key stakeholder use and investment decisions. Fiscal year 2017 objectives focus on analysis and reporting of FCEV durability, range, fuel economy, fueling behavior, and reliability.



Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This project's approach to collection and reporting of data, which has been developed and refined since 2012, has been superb. The National Fuel Cell Technology Evaluation Center (NFCTEC) efficiently processes data submitted to it by vehicle manufacturers. Its approach has resulted in a very cost-effective mechanism to transform raw data into detailed data products (DDPs) and composite data products (CDPs). The Fuel Cell Technologies Office (FCTO) barrier addressed by the project is the first one listed under Technical Barriers in the Technology Validation (TV) section of the FCTO Hydrogen and Fuel Cells Program Multi-Year Research, Development, and Demonstration Plan. However, success of the project's approach, and its ability to deliver outstanding results, are linked with the quality and quantity of the data submitted to the National Renewable Energy Laboratory (NREL). With reduction in the number of manufacturers associated with the project, and the number of data sets provided, NREL is constrained. With reluctance, the reviewer concluded that the project approach requires more robust manufacturer inputs to fully address the barrier, which results in a current evaluation of "good."
- The project approach is technically sound. The project approach is based on FCEVs in use. The project began in in 2012, and the approach changed with the introduction of new FCEVs through the fourth quarter (Q4) of 2017 (54 new FCEVs total). The approach is flexible and responsive to the FCEV marketplace and reports on "lack of current controlled and on-road FCEV data." The approach supports solving the barrier: lack of data. The approach taken leads to FCEV technology validation that the participants use for their evaluations and apply to their business decisions. The approach is modern and current with the needs of the FCEV industry.
- Testing pre-commercial vehicles and sharing data publicly that would not be available otherwise are valuable for auto-manufacturers and the potential buyers. However, given the commercial availability of some FCEVs and the declining number of partners involved, it is positive that this project is tapering down.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project accomplishments are shown through the participation of the automakers and the confidence on their part about the confidentiality of the data management. The NREL evaluation and reporting of the on-road FCEV performance and consumer fueling behavior are very variable—for example, the average fill size (less than two kilograms, which this project studies and reports as absolutely "new, important news"). The accomplishments contribute to DOE goals for the use of hydrogen refueling infrastructure, as they focus on the cars that use the infrastructure. The automakers, likewise, learn more about their FCEVs while "in use" (for a third set of neutral eyes). This project contributes greatly to the DOE goals of car/ infrastructure deployment for hydrogen used in the transportation sector and, from a broader perspective, as a component of H2@Scale.
- The team has done a very good job collecting and publishing data, but little new information and learning have been obtained from the vehicles in the last year. Now that we know that the vehicles are safe and perform according to specifications, it would be better to focus more money on infrastructure.
- Slide 6 starkly displays that the number of original equipment manufacturers (OEMs) delivering data is only half the number it was a few years ago. It is also noted on that slide that not all analysis topics are published, owing to data limitations. Nevertheless, as documented on NREL's poster session display, the NFCTEC seems to be making the most of information at its disposal from three manufacturers. While publication of results for some analytical categories is more limited than before, NREL has taken the initiative to use data for new purposes (e.g., development of a predictive fueling demand model [slides 10–14]). NREL still publishes CDPs consistent with available OEM data and protection of confidentiality. As such, NREL continues to take advantage of previous work to produce cost-effective results.

Question 3: Collaboration and coordination

This project was rated **3.7** for its collaboration and coordination with other institutions.

- NFCTEC is highly regarded and continues to work on maintaining its relationships and credibility with a variety of stakeholders having an interest in the progress of fuel cells and hydrogen fueling. Three OEMs continue to provide data for the project and to work with NREL on the review and approval of its analytical products. It seems there are multiple reasons for the reduction of OEMs contributing to the project. The project was created in conjunction with an FCEV Learning Demonstration Program funded by DOE. With the conclusion of that initiative, some OEMs have evidently determined that the benefits of participation are not worth the cost and effort. Based on the involvement of and coordination with the current OEMs, the reviewer evaluated this criterion as "Excellent." However, if additional OEMs do not resume collaboration with the project, NREL's ability to produce desired CDPs is expected to be further compromised.
- This project has been going on for a very long time. Since then, many stakeholders have been invited to participate, including OEMs, industry, and other organizations. Third-party involvement has been appropriate.
- The poster presentation mentioned the information-sharing with the automaker community. Other collaboration must be considered or already accomplished, but the verbal presentation did not cover this.

Question 4: Relevance/potential impact

This project was rated **3.7** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project continues to be highly relevant as originally designed, refined, and implemented. Fuel cell technology and related hydrogen fueling technology are still being researched and developed. It is possible that reports on progress relative to technical targets continue to be valuable, including for OEMs desiring to assess the status of their products relative to those of competitors. Slide 20 indicates there is a significant

gap between current technology and DOE targets for key FCEV metrics. Particularly, given the relatively minor impact on FCTO's budget, this project's relevance may be as high as for any project in its portfolio. However, the potential benefits are dependent on decisions by others to participate.
- This project is relevant to a number of companies (i.e., automakers and hydrogen refueling station developers). The potential impact could include new designs of FCEV functions and/or new designs of hydrogen refueling stations. This project is also relevant to policymakers because they need to know how practical it is to use the FCEVs reliably, so the policy goals are realistic and represent well-researched questions and summaries. The project includes 54 vehicle types/models, and the related on-road use of all of these vehicles can provide a basis for technology assessment of the industry, projection of future vehicles, and the technical requirements for future hydrogen refueling stations (fueling protocols).
- During the pre-commercial years, this information was particularly relevant to developing safety protocols and refueling standards, standardizing storage pressure, etc. Now that some FCEVs have become commercially available, there is little need to continue to hire drivers to produce results. If data becomes difficult to obtain from that manufacturer, and this information is valuable, ad hoc studies such as TV-149 should be funded.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Most of the future work described on slide 17 is a continuation of familiar, ongoing work using inputs from OEM collaborators, which is reasonable and logical. It is questionable whether it is advisable or desirable to shift the focus of the project "...to reporting on the current market status of commercially available FCEVs, production figures, market analysis, and geographic distribution." Despite the project's positive history, continued relevance, and accomplishments, FCTO should consider phasing it out in the absence of a more substantial OEM commitment and contribution of data.
- The principal investigator mentioned hydrogen station design may be included in the future work plans. Such work, from the NREL perspective and expertise level, is needed to make sure future stations are optimized for performance (fueling protocols and two-way communications: nozzle to car).
- The project's change of focus is appreciated, from reporting on pre-commercial technologies to reporting on current market status of commercially available FCEVs and refueling stations, particularly given that countrywide information is not available elsewhere.

Project strengths:

- This project produces real-world use data of the FCEVs and hydrogen refueling stations from a neutral laboratory. This project is expertly managed, and the results remain consistent over the years (since 2012). This project supports historic data analysis and projections of FCEV performance. From a hydrogen refueling station perspective, this project provides information about station use (frequency, actual fueling, and successful application of the technical fueling protocols). From an industry perspective, this project provides what we all need to make certain the consumer needs are met, both from a vehicle perspective and a hydrogen refueling station perspective.
- The project, as originally designed, refined, and implemented, continues to be highly relevant. The project team at NREL's NFCTEC is exceptionally qualified. It has significant experience and expertise in receiving, handling, protecting, and analyzing data related to emerging fuel cell and hydrogen technologies. The team has credibility and solid professional relationships with relevant stakeholders established over a period of years. The project approach results in products such as DDPs and CDPs, which are valued by many having an interest in the state of fuel cell and hydrogen technologies. Significant results are achieved with a relatively small amount of FCTO's budget.
- This project has a long history of data collection, analysis, and information-sharing. The team is trusted by OEMs to produce valuable aggregated data. Another strength is the team's access to vehicle information.

Project weaknesses:

- The project hinges on voluntary participation from the automakers. The extent to which they participate determines the depth of the work. For those automakers that participate, this project provides an excellent product.
- NREL's ability to produce desired results is constrained by a reduction in the number of OEMs associated with the project and the number of datasets provided. If additional OEMs do not resume collaboration with the project, NREL's ability to produce desired CDPs is expected to be further compromised. In that event, the barrier—a lack of FCEV performance and durability data—will not be fully addressed.
- Since vehicles have become commercially available, there is little need to continue collecting data in the same format and for the same purposes.

Recommendations for additions/deletions to project scope:

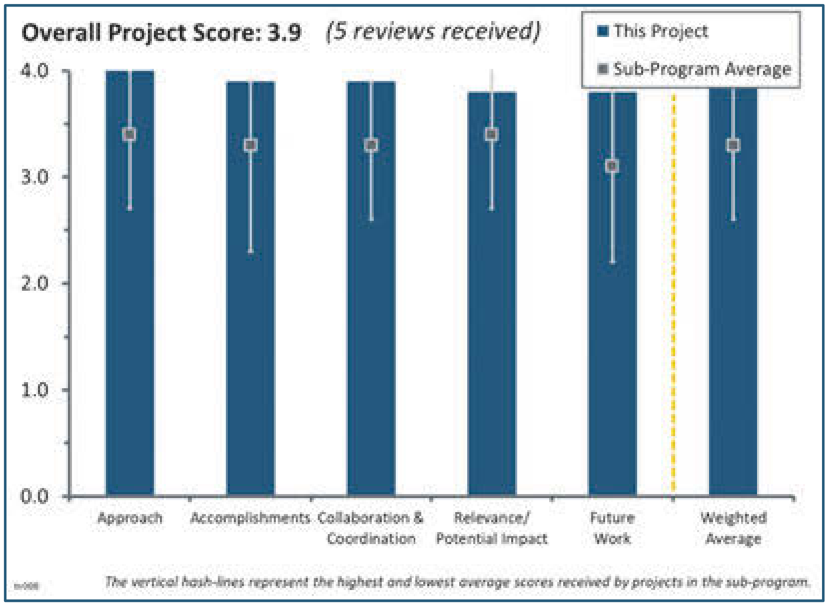
- In the past, this project has been evaluated as "outstanding" across the board by this reviewer. However, FCTO should phase the project out in the absence of a more substantial OEM commitment and contribution of data. If it has not done so, FCTO should assess the merits of a continued, reinvigorated FCEV Learning Demonstration Program. In the process, the Office should clearly identify the factors that resulted in OEM participation and determine whether the conditions causing industry to contribute data can be replicated. Regarding NREL's proposal to shift the project focus from reporting on pre-competitive technologies to reporting on current market status of commercially available FCEVs, the Alternative Fuels Data Center (AFDC) should be tasked with responsibility for providing information on current market status. AFDC is also managed by NREL and already produces numerous reports, publications, and other information on alternative fuels, including hydrogen, and the vehicles which use them.
- The team should add a firm from China. This project should be used to push the envelope of FCEVs released, both in terms of number of FCEVs and FCEV models. It would be interesting to know whether this data can be used to provide designs for hydrogen refueling station developers.
- Proposed future steps are adequate for this project to remain relevant. Focusing on the current status of commercially available FCEVs will be more interesting.

Project #TV-008: Fuel Cell Bus Evaluations

Leslie Eudy; National Renewable Energy Laboratory

Brief Summary of Project:

The objectives of this project are to validate fuel cell electric bus (FCEB) performance and cost compared to U.S. Department of Energy (DOE)/ U.S. Department of Transportation (DOT) targets and conventional technologies and to document progress and lessons learned on implementing fuel cell systems in transit operations. Annual FCEB status reports compare results reported from transit partners and assess progress and needs for successful implementation of FCEBs, addressing barriers to market acceptance.



Question 1: Approach to performing the work

This project was rated **4.0** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project's approach is to compare FCEBs with other alternative vehicles and fuels, validate the fuel cell bus technology, and provide data while the buses are in use. This is real-world service. Comparisons were made between bus lifetimes, the lifetime of the power plant, reliability, the amount of maintenance needed, and fuel economy. The approach of analyzing fuel economy is appreciated since this topic is rarely addressed for alternative fuels; rather, the approach is often to get the fueling station in, obtain vehicles, and pursue customer adoption. The researcher/analyst presented the technology validation data (organized via this project) to transit agencies; the National Renewable Energy Laboratory (NREL) then collected the fueling records from the transit agencies. Compressed natural gas was used as the baseline, and annual reports were given to the DOE/DOT. The approach presented is effective and proactive.
- The barriers that this project addresses are clearly identified. In the Technology Validation (TV) sub-program section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan, they are barrier A ("Lack of Fuel Cell Electric Vehicle and Fuel Cell Bus Performance and Durability Data") and barrier D ("Lack of Hydrogen Infrastructure Performance and Availability Data"). The approach to the work, summarized in slide 4, has been refined and successfully employed for a number of years. Data from transit agencies are collected, analyzed, and transformed into reports on the status and progress of FCEBs being operated at multiple locations within the United States. Information on FCEBs and the data included in the project's 2018 reports are provided on slides 4 and 5.
- The approach is excellent—clean data acquisition, analysis, and presentation. The technology set that makes up this project is about as all-encompassing as possible—that is, excellent. It is critical that the FCEBs be compared to both conventional and newer technologies based on traditional systems. This project now does that. Activities in the maintenance and fueling activities are being tracked, and with sufficient detail to understand where problems occur (balance of plant [BOP], fueling, or fuel cell stack). Overall, the approach is excellent.
- The NREL FCEB testing project continues to be an important avenue for objective data on FCEB performance. As long as FCEBs continue to show viability as a zero-emission bus option (which, as of today, they do), and development of new generations of FCEBs continues (which it is), then this project is the best way to ensure that reliable and objective data on the technology is available for decision makers.

- This project has a reliable and consistent approach.

Question 2: Accomplishments and progress

This project was rated **3.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project's extensive accomplishments are well documented in the principal investigator's outstanding presentation. Summary results of NREL's data-handling and analysis were provided in slides 7 through 14. Detailed reports on a variety of metrics continue to impress, even after multiple reviews of this project. The metrics included in the presentation consist of current and projected numbers of FCEBs, hours accumulated by the fuel cell system for each bus reported on, fuel economy progress and comparisons, hydrogen use and fueling information, bus and fuel cell reliability trends, maintenance costs, comparisons and trends, and issues affecting FCEB performance. The response to prior-year reviewer recommendations (documented in slide 15) is also outstanding.
- This project contributes to the DOE goals of using hydrogen as a transportation fuel as a component of the DOE initiative H2@Scale. The project is based on data and facts, and it validates the technology used by public agencies to provide transportation (six bus fleets) while reducing greenhouse gas emissions. Tracking fuel cell hours (while in real-world service) is important for the overall DOE goal of adoption and proliferation of FCEBs (and other alternative fuels). With the technology validation and application of this work effort, the 33 buses currently on the road provide data and information to support growing fleets (the plan is for 71 buses to be on the road by the end of 2019).
- This project now includes as many different relevant bus platforms as possible to provide a meaningful comparison and, more importantly, to show technology growth in performance and reliability. In addition to vehicle performance, maintenance, fueling, and other normal operations are being tracked. Overall, this project is really outstanding.
- This project is well designed and has been refined over the years, so it is extremely effective at meeting its goals and addressing DOE's goals. There is one small point: on slide 9 for Fuel Economy, it would be good to show the DOE target as on the other slides. Also, on the summary slide (slide 21), it looks like the range target has been met, although that is not indicated.
- This project has excellent accomplishments and progress. In future presentations, the project team should clarify what type of battery electric bus (BEB) is reported on, as currently, the comparison appears to include not only long-/full-range buses but also short-range BEBs versus long-/full-range FCEBs. For added value, the team should mention the technology maintenance readiness level (TMRL) work done. Moving forward, it is recommended the project team also indicate which buses are tested by the Altoona Bus Research and Testing Center—which is a neutral indicator of meeting federal bus requirements.

Question 3: Collaboration and coordination

This project was rated **3.9** for its collaboration and coordination with other institutions.

- NREL has many partners and collaborators who contribute to this project. Since this project was first initiated in 2003, this has worked effectively to cultivate productive relationships. Six transit fleets, located in California, Massachusetts, and Ohio, currently provide operational data, as do hydrogen fuel providers. Bus and fuel cell manufacturers share information on their products. Fleets, fuel providers, and manufacturers all review and provide feedback on documents and materials resulting from the project. As shown on slides 2 and 16, NREL's work is jointly funded by FCTO and the Federal Transit Administration (FTA). FTA's funding supports evaluations of both FCEBs and BEBs. NREL also coordinates and shares information with other organizations with an interest in FCEBs, including the California Air Resources Board and others mentioned on slide 16. The bottom line is that "impressive" accurately describes NREL's credibility and ongoing communications with numerous organizations.
- The collaboration and coordination activities include two major FCEB manufacturers (the only ones) and transit agencies. The presenter mentioned European and Asian FCEB projects but did not mention collaboration with those particular agencies. It is uncertain whether economies of scale can be reached unless bus companies around the world participate in dialogue (and perhaps they already are). The

presenter mentioned that NREL gives "free" third-party certification (for FCEBs) to the transit agencies; the potential here is great and is akin to feeding neutral, third-party input to fuel cell users and leading them to the continued adoption of fuel cells because those users understand the value of the adoption of FCEBs from an analytical point of view.

- The collaboration/coordination involved in this project is appropriate. It is expected that more collaborators and cooperators will be embraced as more vehicles are added to the sample set.
- There are no concerns here; this is a long-running initiative that has established very effective stakeholder engagement processes.
- The collaboration within this project is excellent; there are no comments for improvement.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This FCEB evaluation project makes an exceptionally valuable contribution to (1) documenting the progress of fuel cell buses toward achieving the FCTO bus targets and DOE Hydrogen and Fuel Cell Program objectives; (2) understanding how performance and cost of FCEBs stack up relative to performance and cost of conventional diesel, hybrid, and battery electric buses; and (3) identifying market barriers and technology development priorities. The bottom line is that NREL's results (including analyses, reports, and insights on technical issues) provide much information that is beneficial for those making decisions on investments in technology research and development, buses and related systems, and fueling infrastructure.
- The project evaluates fuel economy using agreed-upon performance indicators. Maintenance workers who work on non-FCEBs are consulted, which strengthens this project, thanks to the knowledge base being tapped, and provides exposure of the maintenance workers to new technologies. The presenter mentioned the steep learning curve for fuel cells. The NREL project will perhaps shorten the time needed to learn about and adopt fuel cells as well as document the items that are evaluated and assessed.
- This project is critically important to understanding the state-of-the-art of the technology, providing information on the status of the technology in the field, and providing critical information to help guide research resources to improve the technology. The impact of this work is huge, aiding a rapid, successful deployment of this technology and providing solid, defensible data to demonstrate to other transit agencies the success of this technology. The only reason this section was not scored as "Outstanding" is because, strictly speaking, this is not low-technology-readiness-level (low-TRL) work (<4). However, it is critically important to inform and help direct early-term research resources (TRL<4) for maximum impact.
- The project is still relevant and offers excellent value. It has been improved by adding in comparisons to BEBs and, more importantly, the coming addition of new buses with current-generation fuel cell bus technology. One ongoing concern about the project is the diminishing return on analyzing technology that is several years old (and in some cases, by companies that are no longer in business). Obviously, that is partly a result of needing long-term lifetimes and reliability data, but it would be good to start getting new performance data from new buses. A risk for the project is that the market is moving definitively toward BEBs as the preferred zero-emission technology, making FCEBs a dead-end technology that does not warrant further data collection. That is something to keep in mind as the work continues, although it seems unlikely that this would happen in the next few years.
- This project is most relevant with many transit agencies considering their involvement and adoption of electric buses.

Question 5: Proposed future work

This project was rated **3.8** for its proposed future work.

- The future for this project looks like more of the same, except with more buses through which to collect data and perform analyses. Slide 19 indicates an expectation of new sites, buses, and designs. With continued funding for the project, increases in transit agencies and buses are anticipated. In addition, slide 18 indicates that NREL plans to introduce the analysis of fuel cell electric trucks this year. Building on its successful model, NREL's proposed future work is reasonable and should continue to provide outstanding value. As suggested on slide 17, NREL is expected to maintain a focus on establishing productive working relationships with additional transit agencies.

- Moving this analysis activity to class 5, 6, 7, and 8 trucks and other heavy applications is the correct growth direction.
- The presentation mentioned the need to evaluate new fuel cell electric vehicle models as they are introduced. Presently, 25 buses (total) are under evaluation. The reviewer did not pick up on the quantity of models under evaluation, but if there are two (one per manufacturer), a greater diversity in models should be evaluated in the future. The researcher/analyst presented a structured (and not very different from last year's) approach, and this could be applied to new models in the future.
- The proposed future plans look good. Getting new FCEBs into the analysis is critical to ensuring that this project continues to provide high value. It is also important to continue the comparisons against BEBs, along with the necessary context to help interpret the data. For example, on a chart like the one on slide 13, it could be a good idea to compare the results of FCEBs and BEBs of a similar age, since the current chart compares state-of-the-art BEBs against both older-generation and current-generation FCEBs, which may be misleading. The bullet points on slide 27 seem to align with this suggestion of comparing buses of a similar age and/or size.
- New interim targets should include a specific year instead of the timeless "ultimate" descriptor. The project team should consider a DOE-funded effort to make the TMRL concept available for trucks and coach buses, in addition to transit buses.

Project strengths:

- The strength of this project includes the comparison between FCEBs and BEBs. The parts supplier availability is also included. On the topic of technology validation, the presenter mentioned that the team "[tried] to get the word out." This dissemination about real-world operations is a strength of the project. Another strength is that this work results in the ability to evaluate fuel cell trucks. Finally, the presenter mentioned that the team planned to transfer this work/knowledge to the light-duty vehicle industry. This frame of mind is very much appreciated because data about the practical use of fuel cells is very much needed. The presenter also works on evaluating new fuel cell technology with "older" fuel cell technologies, both from a research and a validation point of view. In general, this presenter did a great job explaining the team's perspective of technology transfer (knowledge).
- The NREL project team is highly regarded and credible. The team has established great relationships with numerous organizations with a stake in advanced bus technologies. This project has a long-term record of accomplishment. It is cost-effective and provides outstanding returns for a relatively small amount of funding by FCTO. The project's benefit-to-cost ratio is likely as good as, or better than, that of any other project in FCTO's portfolio. The approach to data collection, analysis, and reporting results has been successful and is time-tested. Documentation of FCEB performance and FCEB progress relative to targets is outstanding. Reports of the results are provided to stakeholders through multiple publications and presentations at conferences and briefings.
- This is a well-organized study to collect, track, and analyze performance data of (now) FCEB and (soon) other classes of heavy-duty applications. The project does an outstanding job of this. The collection of data encompasses more than just the vehicle—it includes operational issues as well. The fidelity of the data collection allows for the separation of fuel cell operation and reliability from other systems that are not fuel-cell-dependent, like the BOP.
- The project has a well established and vetted data collection plan with consistency in data collection and reporting. The team also provided stakeholders (such as DOE, DOT, industry, and other policymakers) with objective information on the progress of FCEBs. The dissemination of results is very good. The project has been strengthened by adding comparisons to BEBs.
- This project's strengths lie in its essential neutral data collection and the assessment of bus operational data capabilities, especially since contracted transit agencies and private consultancy firms typically do not have the same neutrality.

Project weaknesses:

- No project weaknesses were identified.
- This project's weakness is DOE and other agency funding.
- While the project provides value in tracking long-term reliability and life of the fuel cell system and buses, that presents a weakness in that the technology being examined is increasingly obsolete—and in some cases, technology from companies that are no longer in business is being used. The new FCEBs coming to Alameda–Contra Costa Transit will help counter that.
- The project did not include the impact of ambient temperature on bus operations and fueling; this is planned for accomplishment in the future. Another weakness of the project is that some fleets have only one bus—this is a fact of the user community and not a weakness of the researcher/analyst.

Recommendations for additions/deletions to project scope:

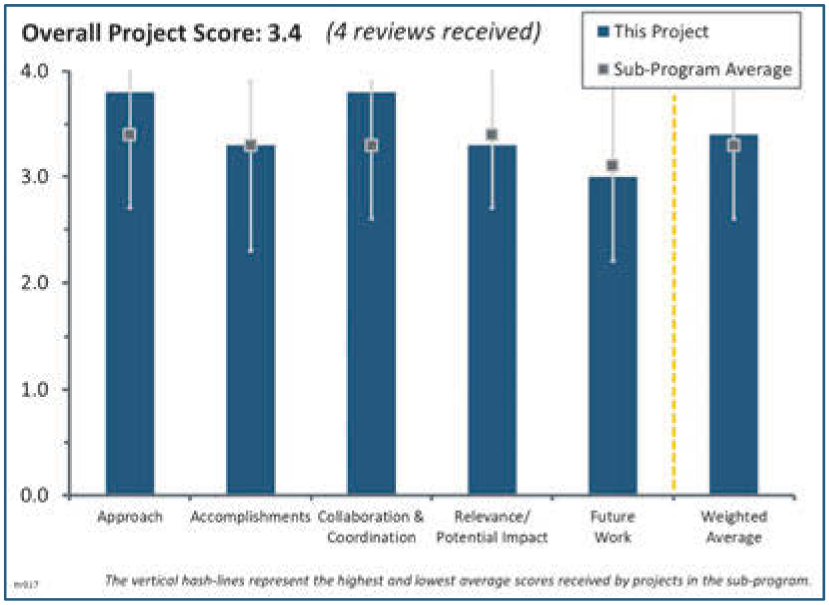
- It is recommended that the FCTO continue support for this project and the future work proposed by NREL. Taking on the analysis of fuel cell trucks would be a good addition to the project's scope. As confirmed by project results (slide 21), some FCEB technical and cost targets have not yet been achieved. During questioning after the project presentation, the reviewer inquired whether the additional work associated with more transit agencies and buses, and the introduction of trucks, could reasonably be accomplished with the "same low price" of $200,000 per year. Some funding increase could be justified.
- It is recommended that the project team consider bus makers from Europe and Asia in future renditions of this project. It is also recommended that the team consider fueling protocols for buses and other medium- and heavy-duty vehicles during the next steps of this project. If protocols that work for all these vehicles can be agreed upon, the use of the FCEBs may increase.
- This project should remain well funded as the industry moves into heavy-duty applications. It is recommended that this work be submitted to the Transportation Research Board's (TRB's) Standing Committee on Alternative Transportation Fuels and Technologies (ADC80) for the January 2019 meeting. The TRB committee has specifically asked for information in this space, and this work does an outstanding job and needs to be put into the TRB community.
- It could be useful to separate out newer FCEBs from the older-generation FCEBs in the analysis, mainly when comparing against BEBs, which are fairly new, and to make clear the different ranges and passenger capacity of the different FCEBs and BEBs.

Project #TV-017: Hydrogen Station Data Collection and Analysis

Sam Sprik; National Renewable Energy Laboratory

Brief Summary of Project:

This project evaluates hydrogen infrastructure performance, cost, utilization, maintenance, and safety. Data analysis supports validation of hydrogen infrastructure, identifies status and technological improvements, provides feedback to hydrogen research, and provides results of analyses for stakeholder use.



Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project requires significant amounts of coordination and collaboration with industry and state entities. At the same time, the project has a high degree of interaction with sensitive business information, which companies are often not willing to share. The project approach has found ways to work within these constraints and receive more data than would otherwise be available for public consumption, while finding ways to protect individual business interests. The approach allows for much-needed information to enter the public domain and be useful for policy and decision makers.
- This project is an evaluation of the level of success of market penetration for hydrogen refueling infrastructure, as well as fuel cell electric vehicles (FCEVs). The information provided is interesting and useful for both automobile manufacturers and the public. This is the only source for countrywide information.
- Data validation is a very important, and a direct approach—just asking/surveying the field—is appropriate.
- Overall, the approach is good, but it is not clear whether collection must continue for all data points (at the risk of collecting data for data collection's sake). Also, the U.S. Department of Energy should consider ending data collection from retail hydrogen stations, as there are more than 100 retail stations in operation in California, and the California Energy Commission pays the National Renewable Energy Laboratory (NREL) through a contract to collect data from all these stations. An alternative could be to give minimum funding if California agencies provide funding for data collection so that NREL can continue to report out at a national level.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Most of the information to track the progress of refueling infrastructures and FCEV penetration is available thanks to this project. It is especially good to see cost information along with performance data.
- Substantial useful data have been collected to understand trends and the reality of the hydrogen workspace. Data on numbers, geographic distribution, and station type are useful. Data on hourly dispensing rates confirm that FCEVs track internal combustion engine vehicles quite closely. The hydrogen price data show a surprisingly large span. It would be interesting to see the price broken down further to determine whether there are trends by geography, station type, or station utilization. As in the past year, maintenance data

identify the compressor as the most cost-impactful element. Causes of failure should continue to be evaluated.

- It is impressive to see the project continue to develop new methods of analyzing data and finding new ways to provide insights on the developing utilization of the hydrogen fueling station network in California. Having said that, the lost opportunity analysis likely requires further refinement. It seems that, as formulated, the projected value really presents the cumulative lost opportunity as summed across all the stations. It does not (and perhaps cannot) provide any information on the counterbalance: the incremental gained opportunity that may have been experienced at one station because of the opportunity lost at another. The cumulative across the network then is likely smaller than presented so far. Still, it would be very interesting if this project could actually provide inside on the net (negative and positive) lost fueling opportunity. It would be interesting to know whether there is any sign in the fueling data, as collected, that customers had to forego using their vehicles for any period of time because of one or more stations' downtime. Such a metric could be very useful to track as an indicator of overall network health. It would also be interesting to see this broken down regionally and on sub-network levels, as the total station network continues to grow.
- The project has provided good added value to the default Alternative Fuels Data Center hydrogen map for retail stations (and has an option to see additional non-retail stations). The number of FCEVs for the first quarter of 2018 is incorrect; NREL should default, like the rest of the industry, to using the California number of FCEVs as posted monthly on the California Fuel Cell Partnership (CaFCP) website, instead of using reports from the California Air Resources Board (CARB), which are released once a year. The issue is that a number of retail stations used in data assessment do not match the time stamp of the total number of FCEVs (the number of stations used by NREL is based on announcements from the California Governor's Office of Business and Economic Development/CaFCP, which are much more accurate with actual numbers). The continued collection of operational FCEVs and fueling stations comes with the risk of collecting too much data that is not essential to understanding technology progress. It would be better for the project team to define "connector/destination" station so as not to confuse viewers of data reported. The hydrogen price should be reported as "passenger car retail price"—this number is used also for heavy-duty (HD) applications, although that hydrogen price is applies only to those projects using passenger car retail hydrogen stations, not HD stations. In terms of missed opportunity fueling, it is unclear whether the point is to publicly point out that if a station is not available, FCEV users go elsewhere to fuel, and there are missed revenues, or if other conclusions should be drawn. It appears that industry is clearly aware this results in missed revenue and FCEV user inconvenience.

Question 3: Collaboration and coordination

This project was rated **3.8** for its collaboration and coordination with other institutions.

- The unique clean-room characteristics of this project's data collection and reporting are likely a key to increasing the amount of collaboration and coordination with industry stakeholders.
- Every station provider is involved, as are organizations that provide support and funding institutions. Furthermore, researchers are open to feedback from industry.
- It appears there is collaboration and coordination with many other institutions, including contracts with the California Energy Commission and CARB.
- The selection of collaborators seems appropriate. Obviously, the station providers have to be consulted. Actively incorporating interactions with listed organizations is also a good idea.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This work is critically important to station network development efforts that are currently ongoing on the ground today. Policy and decision makers, as well as their supporting staffs, are using this data to help track progress and chart the path forward for hydrogen fueling network development.

- As station owners are becoming savvier at installing stations, there are fewer surprises or new learning. However, it is still important to track utilization, safety, station availability, reliability of the components, number of cars in service, and refueling patterns for future generations of station owners and to improve current stations.
- This project is highly relevant to understanding the trends and problems of actual stations.
- The progress assessed serves as a benchmark for public (not industry) awareness about the status of technology. The more widespread the market commercialization of technology becomes, the less relevance NREL’s data collection has.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- The proposed future work is to continue collecting the same data as in the past. This is appropriate.
- The general direction of the future work plan is good, and continuing efforts must be preserved for this project. It was exciting to see some new ideas (such as the opportunity lost analysis presented) for data analysis developed in the past year, and it would have been very good to see more concepts like this proposed in the future work section. It is hoped that expansion of the analysis concepts continues in the future.
- In the future, it would be interesting to see how the reliability of the components and the number/type of safety incidents evolve over time. It is difficult to tell whether reliability is improving or whether the number of safety incidents is changing.
- The project team is cautioned not to collect data for “data collection’s sake”—this is interesting, but it is not necessary to spend federal funding on this.

Project strengths:

- The project’s strength is its unique ability to provide valuable information about the developing hydrogen fueling network; this information is not normally available in the public domain. The project’s ability to balance the information sensitivity needs of individual companies with public data consumption needs is a key part of this.
- NREL is the appropriate agency to collect and aggregate the data. The team has good experience and understanding of hydrogen station issues. The data results are presented in a clear and understandable format.
- The data is free, as disclosing information is required by law. This project consists of many years of data and expertise, and the project team has good data analyses capabilities.
- This project provides insight into the progress made with FCEVs and hydrogen infrastructure.

Project weaknesses:

- The compressor energy usage should be defined, if included (considering the low kilowatt-hours per kilogram dispensed). Certain data should be distinguished. The project team needs to clarify whether the compressor was a booster compressor (if so, the team must identify what compressor energy was used in the central compressor plant where the tube trailer was filled). The team needs to address whether compression moved from low pressure (20–80 psi) to high pressure (+90 MPa). The team also needs to simplify the number of data items collected because of the lack of root cause information explaining the story behind the data collected.
- Data is sparse on everything except tube-trailer-delivered-hydrogen stations. This is because there are very few stations that do anything else.
- It is not likely that new future innovations will be generated from the data since station owners have plenty of experience at this point.

Recommendations for additions/deletions to project scope:

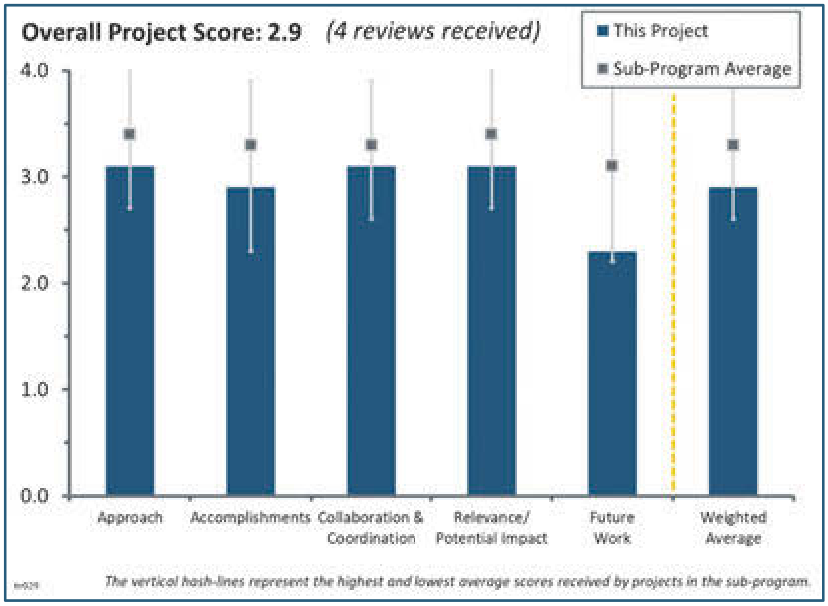
- The project team should look into the differences between various types of hydrogen stations and whether trends/differences can be correlated. The electricity price (cents per kilowatt-hour) shown in the backup slides is very high—this should be further explored/explained.
- The project is encouraged to continue development and expansion of creative new data analysis concepts to continue providing new insights into the evolving operation of hydrogen fueling station networks.
- In the future, it would be good to see how component reliability and safety evolve over time. It is difficult to tell whether reliability is improving or the number of safety incidents is changing.
- There were a limited number of data points collected.

Project #TV-029: Performance and Durability Testing of Volumetrically Efficient Cryogenic Vessels and High-Pressure Liquid Hydrogen Pump

Salvador Aceves; Lawrence Livermore National Laboratory

Brief Summary of Project:

This project explores the potential for reaching high volumetric (50 g H_2/L target) and gravimetric (9% H_2 weight fraction target) storage performance within a small (63.5 L internal volume), high-aspect-ratio (34 cm outer diameter and 100 cm length) cryogenic pressure vessel with long durability (1,500 thermomechanical cycles) refueled by a liquid hydrogen (LH2) pump to be tested for degradation after delivery of 24 tons of LH2. Cryogenic pressurized hydrogen storage and delivery provides safety, cost, and weight advantages over alternative approaches to long-range (500+ km) zero-emissions transportation.



Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The team has a good approach to proving the safety and performance of the cryogenic vessels that will extend the fuel cell electric vehicle (FCEV) range.
- The approach combines testing the pressure vessel and the pump into the same series of tests, so it is economical in terms of the number of tests required. Although boil-off was mentioned in one of the slides, there was no specific discussion of the boil-off performance and potential for loss of fuel from the hydrogen storage system due to boil-off. It would be good to understand those items as practical concerns when using this technology.
- Technical barriers addressed by this project are among those documented in the Technology Validation sub-program section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP). The project has also dealt with barriers identified in the Hydrogen Storage sub-program section (for example, barriers A, D, E, J, and N) and the Hydrogen Production and Delivery sub-program section (barriers C and H) of the MYRDDP. This underscores the interest and joint funding by three Hydrogen and Fuel Cells Program [former] sub-programs. If the sole evaluation criterion were the number of liquid hydrogen barriers associated with the project, it could be viewed as "Outstanding." The reviewer's knowledge of cryogenic vessels and liquid hydrogen technologies is limited. The project's approach seems reasonable. However, the number of tests, equipment tested, and test results seem minimal in the context of the project's cost and the four-year-plus time period.
- This project suffers from an unclear approach toward the topics it seeks to address. The project's proposed tasks are intended to address infrastructure and hydrogen storage, yet they miss several opportunities to investigate all applications of the technology from a singular focus toward onboard vehicle storage. The project does not address the impact on other methods of using cryogen-compressed (cryo-compressed) technology in other aspects of the infrastructure.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Test facility construction and commissioning and pump model development and validation are key project accomplishments. Both of these accomplishments will have significant value for future testing and design work and will hopefully be available to companies trying to design and bring to market systems that are related to LH2 fueling and storage.
- The team has made excellent progress, and the project is complete.
- The information on accomplishments could have been enhanced by (1) providing more specific data (e.g., on durability metrics) resulting from cycle testing the BMW cryogenic vessel prototype, (2) citing quantified results linked to selected barriers that are deterrents to the commercialization of LH2 pumps and storage vessels, and (3) indicating what accomplishments have been achieved during the final year of the project, i.e., since the last Hydrogen and Fuel Cells Program Annual Merit Review (AMR). As noted in the "Approach" section, accomplishments are limited, given the project time period and cost. During a poster session discussion with the principal investigator, Dr. Aceves, it was stated that data collection days at the hydrogen test facility during the past year were "about the same" as 19—the number of days cited at last year's AMR.
- The value returned for this project is poor in comparison to the overall cost. The project's accomplishments provide information but lack analysis and useful information to facilitate the next phase of development or technology transfer.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The project partners—Spencer Composites Corporation, the Linde Group, BMW, and Lawrence Livermore National Laboratory (LLNL)—have been collaborating for an extended period, on both this and other projects. Together, the partners have developed, contributed to, and utilized an integrated and capable hydrogen test facility at LLNL.
- The team has a good balance of partners with the necessary technical capabilities.
- While the project worked well with the collaborators, there was a good deal of defensiveness in the answers to the reviewer questions from the previous year; it seems like there is an "us versus them" mentality, as opposed to "let us solve this since we are all in it together." That said, the larger issue of a holistic exploration of LH2 fueling/vehicle storage is beyond the scope of this project.
- The project does not cite any collaborators beyond those who already have a deep understanding of the technology. Collaboration with skeptics of the technology and a more diverse group of stakeholders would facilitate more impactful and relevant accomplishments.

Question 4: Relevance/potential impact

This project was rated **3.1** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project aligns well with DOE goals to increase FCEV range. This solution is focused on light-duty vehicles but would still be an excellent fit for medium- and heavy-duty vehicles. LH2 could be a significant benefit for larger vehicles that need longer ranges for commercial viability.
- The potential benefits of LH2 fueling/vehicle storage as described by the investigators here are significant. There needs to be an umbrella project, of which this would be a sub-project, that covers all of the elements needed to enable the use of LH2 to directly fuel vehicles. Recognizing that the issues of the vehicle fueling interface and boil-off control are beyond the scope of this project, it would be helpful to briefly summarize the approaches; otherwise, this project could be considered isolated, instead as part of a practical infrastructure-dispensing vehicle system.

- There seem to be disparate conclusions by individuals who do have the requisite expertise. The LLNL team makes a case for relevance—in reality, however, the relevance of this project, or ones like it in the future, is linked to LH2's potential economic viability, safety consideration, and commercialization prospects.
- This project has tremendous potential impact and is very relevant to the development of infrastructure, yet this impact and relevance are not realized.

Question 5: Proposed future work

This project was rated **2.3** for its proposed future work.

- The proposed future work should focus on the promulgation of the results and technology transfer to improve the impact of the project. The technical topics cited are good, but they are not as important as better promotion of the impact and analysis that demonstrates all of the potential uses of the technology evaluation.
- While remaining challenges and barriers are cited, no future work is proposed. The project's scheduled completion is June 2018.
- The project has ended, and no future work is planned.
- The project is complete.

Project strengths:

- The project has benefitted from intellectual and cost-share contributions by industry partners. A LH2 test facility has been built and is available at LLNL.
- The project team has developed excellent test facilities and modeling capabilities. The team has provided useful durability data on two key elements of a LH2 fuel system.
- The technology demonstrated is progressive and very relevant to the commercialization of FCEV infrastructure.
- This project consists of excellent team capabilities and collaboration. The validation of LH2 tanks for vehicles could help increase the range to make them more commercially acceptable.

Project weaknesses:

- The project needs to better explain the practicality of the system being tested, in terms of its interfaces to infrastructure and vehicle systems. For example, it is not clear what happens to the fuel available in the vehicle if it is parked for an extended period of time, or whether boil-off/latency renders the whole idea impractical. Also, the question remains whether the fueling nozzle/receptacle system for cryo-pressure fueling is practical for consumer use.
- The tank takes up considerable space that limits the ability to carry cargo. This technology would be well suited for larger vehicles that could benefit from the added range, with minimal impact to the cargo area (e.g., SUVs, vans, trucks—including light-, medium-, and heavy-duty vehicles).
- The project concept and approach seem to have merit in addressing important barriers to the adoption of LH2 technologies. However, project implementation has had minimal benefit, in terms of actually removing barriers.
- The project is weak on analysis and on the promotion of technology potentials.

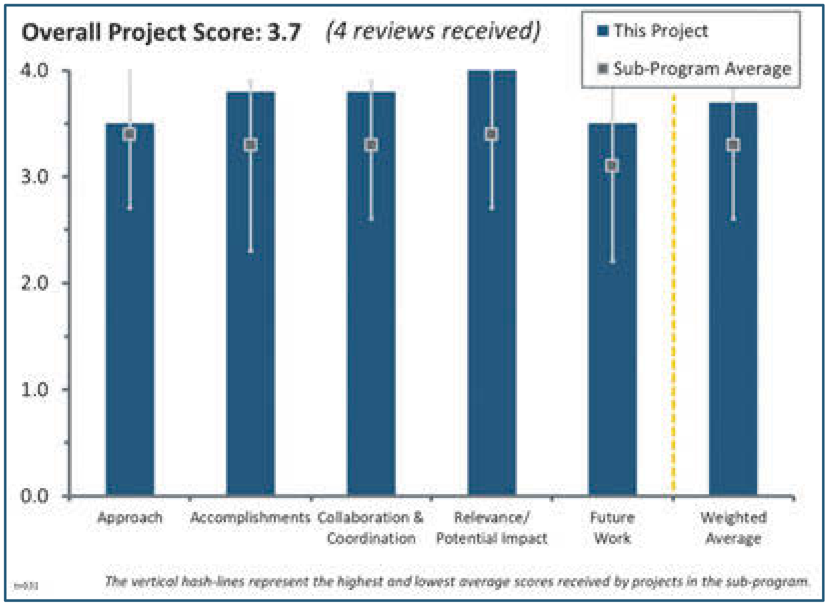
Recommendations for additions/deletions to project scope:

- There are no recommendations for additions or deletions related specifically to the project, which is concluding. The DOE should assess whether the LLNL hydrogen test facility has value for other LH2 development and testing activities. Slide 11 cites and responds to a prior reviewer comment, specifically: "The issue of LH2 feasibility should be addressed by DOE before any further investment in similar testing and validation. LH2 may have potential advantages, as suggested by the project team. However, an objective, hard-nosed, comprehensive assessment of the current state of technology, and technology prospects, should be done prior to making another significant investment in validation of selected components." If it is not already doing so, FCTO should consider such an independent assessment. Perhaps this could be assigned to the Hydrogen and Fuel Cell Technical Advisory Committee.

- This project has ended; however, it would be valuable to have a follow-up project to address the remaining barriers listed in the presentation:
    - Demonstration of pump performance versus fill pressure
    - Demonstration of solutions for long-term vacuum stability
    - Demonstration of rapid and inexpensive manufacture of cryogenic vessels
- It would be helpful to know more about the LH2 delivered to the station to the vehicle usage sequence to better understand how cryo-pressure storage might be part of a practical commercial station and vehicle application.

Project #TV-031: Dynamic Modeling and Validation of Electrolyzers in Real-Time Grid Simulation

Rob Hovsapian; Idaho National Laboratory



Brief Summary of Project:

This project is demonstrating the fast-reacting performance of electrolyzers and characterizing the potential and highest economic value of their installation to enable participation in energy markets and demand response programs. A novel approach of distributed real-time simulation is used, with electrolyzer hardware at the National Renewable Energy Laboratory (NREL), in conjunction with power system simulations at Idaho National Laboratory (INL).

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The presenter provided a comprehensive review of information and gave confidence that a full review of existing electrolyzer information, including hardware in the loop, was conducted. It is very important to have real-world utility input. The hardware with digital blueprint, covering connections across multiple locations, allows for a good use of resources and a better understanding of incoming resource allocation and grid impacts/benefits. A key element is allowing the front-end controller to prioritize communication from multiple systems and signals that can be translated to electrolyzer language for best operation.
- The authors have already presented localized analyses (as on the "economic benefits to states," slide 17) of hydrogen production costs for the "typical" electrolyzer operation case (no demand response and no grid services) across the entire nation. This is highly valuable information. At the same time, the project is looking to leverage highly specific and high-resolution data, analytical methods, and experimental validation for localized cost analysis of production; this includes demand response and grid services in certain case studies. While the same resolution cannot be expected for the state benefit analysis to include grid services and demand response in all locales, it seems that a sufficiently expanded set of case studies should provide insights into developing a set of heuristics that could give a rough approximation of hydrogen costs across all the nation, when these services are included. There is currently no similar effort outlined in the approach, but it would make a useful addition.
- There is a good use of simulated profiles based on actual utility data and recognition of the need for interface and controls to effectively communicate between the electrolyzer and the source. There is a good description of the need for different timescale responses on the controller.
- The development of grid simulation hardware is an excellent approach and allows for a much broader range of test conditions and scenario tests than can easily be done in a field test.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The vendor's neutral approach will allow for application by multiple organizations and shows major progress toward the goal of widespread adoption. This is a great accomplishment, versus focusing on just a single proprietary partner. There is outstanding progress on this project, with three out of four milestones complete, including two tasks (G1 and G2). The effort appears on track to finish all promised work. The team will need some additional run time and real-time testing, but all tasks should be done before the end of the project in 2018. Proving the equipment and communication protocols will require 200 hours of testing and 500 hours of testing events, given the complicated hardware and control schemes. Economic assessments show the project meeting zero-carbon hydrogen production options at $4/kg. The demand response is more than fast enough to meet signals from utilities, proving confidence and applicability of the technology.
- The progress to date is very good. The breadth of evaluation across the United States is particularly impressive, as this provides industry with critical information into strategic planning on how, when, and where we can anticipate the early adoption of this technology, as well as the likely impact and value to the grid operators.
- The data that are coming out of this project should help build solid business cases and analysis, based on reliable and trustworthy data sources for policy and decision makers. This work is the first of its kind and is going a long way to meet critical information needs.
- Controller design is an important accomplishment; it would be nice to actually see electrolyzer data or profile data to help with understanding how much the signal varies and how the electrolyzer responds.

Question 3: Collaboration and coordination

This project was rated **3.8** for its collaboration and coordination with other institutions.

- The project includes inputs from utilities (Pacific Gas & Electric, plus three others), multiple laboratory inputs from INL and NREL, and inputs from both Florida State University and California State University, which help in workforce development. California Air Resources Board input and a deep understanding of results both show extraordinary cooperation. Just the hardware build and system programming, along with the electrolyzer and equipment design build, show outstanding coordination and leadership in bringing together multiple organization cultures to meet goals on time and within budget.
- The engagement with the utility sector is an almost-unique aspect of this work. The real-grid-data-sharing is a critical piece of what makes this project likely to have a high impact, as decision makers will likely see significant added value in the validation with real-world grid operation dynamics.
- The description of collaboration with utilities, with specific descriptions of interactions, is good. Getting actual utility data for the models provides much more credibility to the results and the technical approach.
- A broader evaluation of the testing by the power utility industry representatives is recommended. It would be interesting to see if the utility industry agrees on the characteristics of the testing/simulations with respect to slow and fast response. These tests need to be representative of typical best/worst case scenarios and validated by the utilities. In the end, the value that this brings to the grid needs to be quantified. The direct impact on reducing hydrogen costs by taking advantage of demand response is only part of the value to the utility. The question that remains is how to put a value on the effect that the electrolyzer has on the power grid, with respect to frequency and voltage regulation, as well as the grid impact of having large-scale demand response capabilities.

Question 4: Relevance/potential impact

This project was rated **4.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is extremely relevant to California and any other states that are going to move from 30% variable renewable energy generation to 50%. Grid management is one of the major challenges to deep decarbonization. The open nature of the hardware will ensure widespread adoption beyond the United States to other countries with deep decarbonization plans and efforts. This will also allow lower-cost hydrogen production and accelerate zero-emission vehicle updates.
- The sustainable future of low-cost hydrogen is contingent upon understanding not only how grid-generated hydrogen adds value as a fuel or a feedstock but also how it adds value to the grid through storage and grid resilience. The outcomes of this and similar studies can help implement hydrogen as a mechanism to allow for further penetration of renewables, making all grid activities (including battery electric vehicles) more renewable. As such, it is important that we develop tools to determine the additional value to the grid that such services provide; it is strongly recommended that the team consider methods to quantify all of the value this can bring to the utility.
- This type of information is highly relevant to H2@Scale. Concrete demonstration that the electrolyzer hardware can actually serve this application is important, as it lends credibility for moving forward with the installation of large electrolyzers.
- This project is filling a critical information gap.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The project team's future work is relevant. The team will finalize project milestones by testing higher renewable energy penetrations and will work with Arizona state utilities, where there may be the largest single-point transportation fuel demand in the near future. Further exploration with other electrolyzer manufacturers will be key for proving the value of the open-source approach, as well as adoption outside of the laboratory-funded test demonstration project.
- Future plans are reasonable, and next steps are needed to provide a well-rounded picture across different geographic regions.
- The next phases of testing and validation are anticipated. The test plans look sufficient.
- There was mention during the presentation that the front-end controller allows coordinated aggregation of responses from multiple units to respond to utility grid demand signals. The concept appeared to be that several units could act in a coordinated fashion if the demand signal was greater than the individual units' capabilities. However, there did not seem to be any discussion of results or plan for future work with this concept. This seems like a very interesting aspect that should be included in the future work plan. Additionally, there should be other opportunities identified for electrolyzer operation in the project's scheme other than just renewable generation response. The potential for reaction in grids with low renewable energy generation, the reaction in emergency response, and the reaction on different grid scales (perhaps down to microgrids) could be useful in helping build additional cases for decision makers.

Project strengths:

- The strengths of the project are the potential impact with decision and policy makers and the information gap that this work is filling. These concepts are currently active in several discussions and planning meetings, deliberation gatherings, workshops, etc. The availability of this information is positive, especially the technical potential for electrolyzers and the business case analysis, which are crucial parts of the conversation.
- Major strengths are the coordination of key stakeholders and the addressing of a pressing problem of large-scale renewable energy and grid management. The open-source hardware and pursuit of multiple

electrolyzer vendors are outstanding. Workforce development through participation with state universities such as California and Florida also give value that is often overlooked.
- There is a good tie to energy demand maps and utility profiles. Controller development is a highly valuable achievement to enable these simulations. Challenges were well addressed.
- The development of the test hardware is a critical step in this development, and the progress to validate this has been quite good. The project brings high-value data and analysis to industry.

Project weaknesses:

- There were minimal weaknesses identified.
- One of the project's weaknesses was the validation of testing protocols; the project would be strengthened by having an independent evaluation of the test protocols by a broader cross-section of utility operators. Establishing a method to determine the value of voltage/frequency regulation to the utility is an important need. A comparison on a cost/performance basis of electrolysis versus other technologies to regulate the grid would be an important outcome. It is not apparent that electrolysis is the best solution to utility regulation and demand response. Quantifying and comparing with other technologies would be an important outcome.
- The only weakness of the project is that detailed analyses should have been completed for more locations. However, this seems more of a fundamental limitation of time and resources available than a weakness in the project's execution.
- It would be helpful to include more actual (unallocated) data.

Recommendations for additions/deletions to project scope:

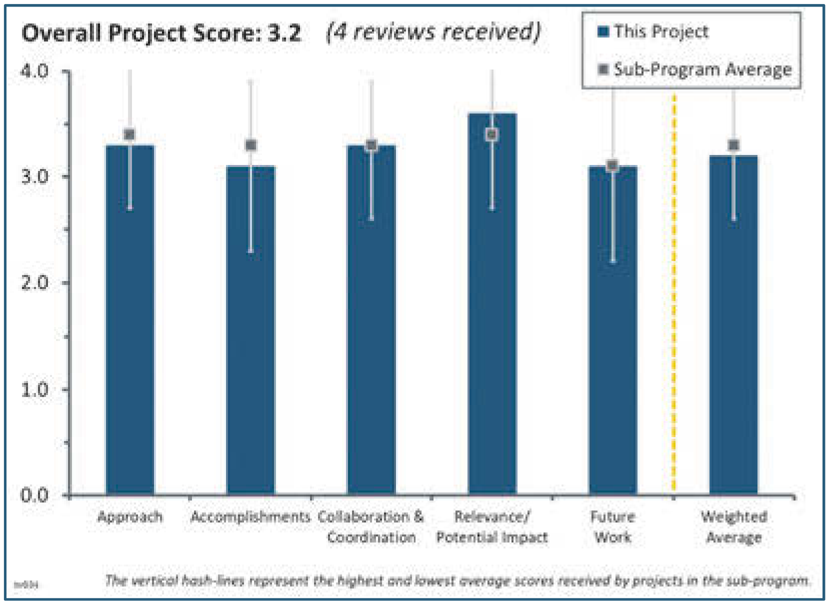
- If possible, it is recommended that the project add a comparative analysis of the technical and economic potential of electrolyzers to achieve the combined grid and transportation benefits investigated in this work, as compared to other technologies (battery storage, vehicle-to-grid and vehicle–grid integration, ultracapacitators, flywheels, etc.) seeking to achieve the same goals in various usage cases (including addressing high renewable energy penetration on the grid).
- It is recommended that the project increase the scope to work with the Arizona utility and other electrolyzer manufacturers and vendors to implement control communications hardware to the interface between the utility and the hydrogen production equipment.

Project #TV-034: Fuel Cell Hybrid Electric Delivery Van

Jason Hanlin; Center for Transportation and the Environment

Brief Summary of Project:

This project aims to increase substantially the zero-emissions driving range and commercial viability of electric drive medium-duty trucks by integrating a hydrogen fuel cell into the powertrain. Investigators will develop and validate a demonstration vehicle to prove its viability and then build and deploy up to 16 vehicles, which will perform at least 5,000 hours of in-service operation. The project will also develop an economic and market opportunity assessment of medium-duty fuel cell hybrid electric trucks.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The overall approach is excellent and consists of retrofitting a delivery van for fuel cell electric vehicle operation, shakedown testing, and demonstrating successful operation before moving on to producing an increased number for field demonstration, while making incremental improvements/changes in existing electric vehicle technology for the conversion.
- Both the approach and the planned work are sound. Developing a kit that can be used for new trucks and the conversion of existing trucks will help to commercialize the technology within this application (or similar applications). Two years is a sufficient amount of time to validate performance.
- This project has been very slow to progress, but the team does seem to have effectively addressed the issues that were causing delays, and there is a plan for moving forward onto the next phase. Fortunately (or unfortunately), the market for electric trucks has not progressed very quickly, so the project can still provide value. The ability to test the fuel cell van on routes with a range of other technologies is a major strength of the project. The need to develop a market study is questionable, however, as that is something that can be done by market analysts. The real value here is in developing and testing a vehicle and making the results available.
- The project has a reasonable approach. Owing to current delays with integration, the December 2018 milestone for the go/no-go decision point appears optimistic, as the integrator still needs to figure out the issues of the first prototype vehicle. It is recommended that the project team put more burden on the vehicle integrator to prioritize the development, testing, and operational support of newly developed components (direct-current–direct-current [DC-to-DC] convertor, etc.). This is to ensure that these components work and, if issues arise, that resolution receives internal priority.

Question 2: Accomplishments and progress

This project was rated **3.1** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Although the project has had early issues that caused the schedule to slip, the team has made significant progress over the last year. The prototype truck will be on the road and in service in the next few months.
- The project aligns well with DOE goals. Progress has been slow, but the project appears to be finally poised to begin demonstrations; therefore, progress has occurred on that front.
- There is good progress; however, it would be good to see that the rate of development and testing is accelerated/prioritized wherever possible for the next period. The truck is on-road as of the DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review, per the reference made during the presentation and the shared video (per the presenter making this available to those interested).
- Progress on this project has been slow—mostly because of delays in long-delivery items and in the custom DC-to-DC converter build-out. It is not clear why the build-out decision was made. It seems as though that could be an Achilles heel; it has caused delays and is a point of challenge in that it has not been field-tested for this application.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The project has excellent partners that include solid original equipment manufacturers and a demonstration partner that can put the truck into service to validate performance.
- The collaborators/coordinators are good and appropriate for this project.
- It seems as though the project management of the partners improved over the past year.
- It is not clear whether United Parcel Service (UPS) was present and directly involved with other areas of integration, outside of the high-voltage and low-voltage wiring review. UPS staff could have acquired significant understanding of the vehicle system and have had even better insight and ability to support test the first vehicle.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The successful completion of this project is excellently aligned with the relevance and impact of developing and demonstrating a fuel cell powertrain in this application. The precise balance between the energy stored in the batteries and in the hydrogen is an optimization issue that is dependent on the cost, performance requirements, and duty cycle of this application. There are other projects addressing the optimization issue as part of this overall Program. It is suggested that the team look into optimizing the power systems after successful demonstration of the technology.
- This is a highly relevant and potentially impactful project because of the increased understanding of the operational range limitations of battery electric options in last-mile delivery vehicle space for medium-duty vehicles.
- The project aligns well with DOE goals and will help accelerate market growth for fuel cell technology in medium- and heavy-duty applications.
- The project still aligns well with DOE goals in supporting the development of fuel cell commercial vehicles.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- It is good to see that there is adequate funding to support six vehicles. Even if the original goal of sixteen may not be reached, six vehicles should still be adequate to provide useful data. The key is to keep the project moving. Further delays could make the technology developed under Phase I begin to look fairly obsolete by the time Phase II rolls around.
- The proposed future plans are good. However, given the delays in Phase I, it is suggested (in keeping with a previous reviewer comment), assuming a successful build, that the length of the demonstration of Phase I hardware be shortened and the number of vehicles in Phase II be reduced by a factor of two. The training of drivers and first responders is important, but when completed, this vehicle will (or should) operate in parity with conventional vehicles—purchasers of the Toyota Mirai do not get training.
- The future work is well planned to accomplish project goals. A six-month demonstration should be sufficient to evaluate the pilot truck, but there is concern this will not start soon enough to meet the go/no-go decision point of 2018.
- It is unclear whether the Linde Gases station in West Sacramento is ready to receive and facilitate the fueling of the first vehicle or if a number of steps still need to happen on the operational side (outside of training and fueling agreements). It would be good to hear that the project includes the effort of Unique Electric Solutions (UES) to accelerate the testing of the unproven DC-to-DC converter and verify the capability of this component. The DC-to-DC converter appears to be the wildcard component for the functionality of this vehicle. Fueling training time appears overly conservative, as Toyota Mirai drivers do not receive much, if any, fueling training.

Project strengths:

- The project is well-thought-out and should result in a positive outcome. When successful, it will be a powerful demonstration of this technology to the end users/operators of the parcel delivery industry. The commitment of some of the partners (for example, the Center for Transportation and the Environment) in ensuring that financial resources are available for completion is notable.
- This project has a good team with the right balance of capabilities to execute the project, proving that fuel cell technology in this application can be carried into other medium- and heavy-duty truck applications. The economic assessment planned will be a valuable input to the industry.
- The project concept is still valid, as there is a real need to find zero-emission technologies that can meet the demands of a typical delivery van. It appears that the van will be tested on different types of delivery routes, which is also a strength. Although the need to develop a DC-to-DC converter for this van was the cause of major delays, this may end up as a net positive if the converter works well.
- This project's strength lies in fuel cells as range extenders in medium-duty last-mile delivery vehicle service. Both the collaboration with UPS and the use of actual route data were also strengths.

Project weaknesses:

- The uncertainty of full funding for the second phase of the project is unfortunate. Even with the smaller number of trucks, the project is expected to provide valuable input to the industry.
- Most of the problems with this project appear to be mostly out of the project management's control. With that said, it would have been assumed that mitigation measures would have been put in place to mitigate these issues. For example, labor and administration costs during delays should have been anticipated and a contingency put in play.
- The project's weaknesses lie in the delays in getting to the demonstration phase, the limitations of infrastructure availability, and the funding shortfalls. It will be important to stay on schedule over the next year. It may be that the six-vehicle demonstration is sufficient and the full sixteen vehicles are not needed, but this work does demonstrate the risks of funding a project in which the partner providing matching funds can withdraw its commitment so readily.
- The DC-to-DC converter has so far been untested. Funding for the next project phase is undetermined.

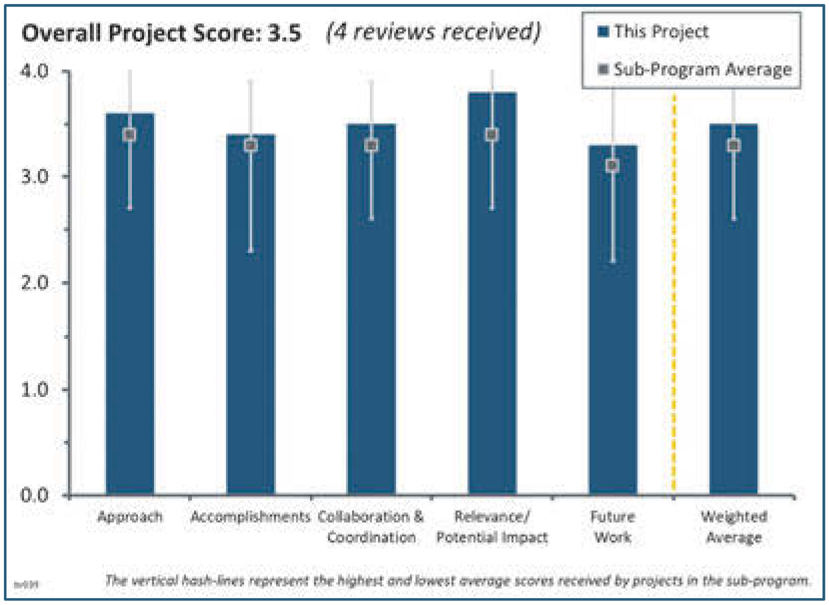
Recommendations for additions/deletions to project scope:

- There are no recommendations for Phase I, but the Phase II plan could potentially leave out the market study and focus only on the demonstration, data collection, and data analysis.
- Assuming successful vehicle completion, it is recommended that the length of the shakedown/demonstration for Phase I be shortened and the number of vehicles in Phase II be reduced by a factor of two. Also, it is recommended that this team consult with Argonne National Laboratory to optimize the energy storage and powertrain split between batteries and hydrogen to produce an optimized balance consistent with performance requirements, driver expectations, etc.
- The project team should address whether it is feasible to switch to 700 bar hydrogen tanks for added range. This would also lead to more fueling opportunities with current stations in California. The team should encourage the integrator to commercialize the new/custom DC-to-DC converter. This could help alleviate issues with parts availability and potentially lower future cost.
- It is recommended that the project team accelerate testing and that UES prioritize solving issues with the custom DC-to-DC converter.

Project #TV-039: Innovative Advanced Hydrogen Mobile Fueler

Sara Odom; Electricore

Brief Summary of Project:



The objective of this project is to design and build an advanced hydrogen mobile fueler (AHMF). The developed mobile fueler will be deployed to support a network of hydrogen stations and vehicles, and fueling data will be gathered for analysis by the National Renewable Energy Laboratory (NREL) Technology Validation Team. To reduce risk, the mobile fueler is based on an existing conventional station design, and project efforts are coordinated with station providers and automotive manufacturers.

Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- Mobile fuelers are a great way to kick-start the buildout of a fueling infrastructure. There have been a number of mobile fuelers developed in the past. This concept uses proven existing hydrogen fueling station concepts and hardware and fits on a flatbed 45-foot trailer. This station has already been designed to satisfy the SAE International (SAE) J2601 fill protocol, and SAE 2719/International Organization for Standardization (ISO) 14687 fuel quality specifications with a point-of-sale system. This concept/approach to the development of a mobile hydrogen fueler is excellent. The approach is well-thought-out and clearly developed by a team that has experience in these types of projects.
- The approach includes how the refueler will support the lack of hydrogen refueling backup in the northeastern United States. The approach stands to solve the technical issues of hydrogen storage on board a trailer. The approach is based on codes and standards. The specifications were approved by the U.S. Department of Energy (DOE), the components selected, and long-lead-time components ordered, and the final design documents were also approved by DOE. The Hydrogen Safety Panel reviewed this project, and initial hazard analyses were completed.
- This is an excellent plan to address the barrier of hydrogen access for light-duty fuel cell electric vehicles (FCEVs).
- The project approach looks reasonable. For future presentations, the principal investigator (PI) should mention capability to plug in the fueler to 480 V, three-phase to run the compressor, instead of relying on a diesel generator to provide power.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This project addresses energy consumption of the mobile refueler, which is an overarching DOE goal. The DOE goal of hydrogen infrastructure buildout is addressed, for when completed, the project (trailer/ refueler) can be used to educate hydrogen producers, testers, and users about codes and standards for mobile refueling. This project contributes to the DOE H2@Scale approach: transportation component (the

plan is to be able to fill 20–40 cars daily). Regulatory requirements for transporting hydrogen on U.S. roads, at least in the Northeast, will be discussed and resolved with this project (addressing regulatory barriers and the goal of addressing any unreasonable barriers).
- Largely, the project is on schedule, making excellent progress and not withstanding a small delay because of the liquid nitrogen (LN2) cooling system design effort. However, it is probable the overall system and operation will be better. This should not be a major issue, and the project will finish as scheduled.
- The team has made excellent progress toward meeting project objectives. The project has had no significant delays to the schedule.
- In addition to energy consumption reduction, use of LN2 also helps with economics. It will be interesting to hear whether the U.S. Department of Transportation (DOT) approves a special permit, which will benefit the industry at large if approved. Slide 8 indicates the trailer is not delivered, which appears to conflict with slide 9 information that the trailer is 95% complete.

Question 3: Collaboration and coordination

This project was rated **3.5** for its collaboration and coordination with other institutions.

- The team has a good balance of technical expertise from original equipment manufacturers and consultants. It will be good to see the addition of a site partner for demonstration. Selecting the right location/partner will be important to ensuring success and gaining acceptance of this hydrogen fueling technology.
- The project has exactly the right number and type of collaborators to ensure a successful project execution.
- It appears collaboration and coordination are well covered. The PI could possibly consider collaboration with the California Department of Food and Agriculture Division of Measurement Standards for preliminary discussion about metering and meter calibration on a mobile fueler.
- The planned collaboration includes NREL (data collection), automotive companies (Toyota was mentioned), the Hydrogen Safety Panel (Safety Plan review), DOT (permitting), and a tank company (Hexagon Lincoln was in the report but not the verbal presentation). The team needs to conduct more outreach. Perhaps the team could contact hydrogen refueling station developers, metering agencies, and automakers. It is unclear whether there can be a common approach for quality testing and evaluation of metering in the states where hydrogen infrastructure is being rolled out.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Developing mobile fuelers is an excellent way to help kick-start the deployment of a hydrogen fueling infrastructure. They can be used to augment stationary hydrogen fueling stations and provide redundancy when needed. Indeed, mobile fuelers make up a major part of other countries' strategies for early deployment of a hydrogen fueling infrastructure. The relevance of this project/concept for strategic hydrogen fueling infrastructure deployment is extremely high. Indeed, this project will be establishing new permits (DOT exemption for high-pressure hydrogen transport) and construction of high-pressure (95 MPa) hydrogen transport cylinders that can be used in the future by other similar activities. This is excellent.
- This project is relevant as a backup and emergency fueler for the hydrogen refueling infrastructure in the northeastern United States. The need for backup relates to potential station downtime when the cars are introduced in the Northeast. The goal is to use the refueler to support stations beyond 2020. The team plans to release the refueler in 2019. The refueler can be a model for others to follow, as more refuelers will be needed in the United States with the proliferation of FCEVs.
- This is an excellent project with significant potential impact and relevance—particularly the DOT special permit and the ability to reduce the packaging/footprint size of a small hydrogen station.
- This project is well aligned with DOE goals and objectives. Providing access to hydrogen fuel is extremely important to gaining public acceptance and increasing awareness.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The project is under way to meet the 2019 deployment. The project managers report cost overruns, so more attention is needed for cost accounting in future work. The future work reportedly includes coordination, testing, and evaluation with a Nationally Recognized Testing Laboratory in "preparation for listing," which entails completing the design, equipment procurement, and refueler operation. It seems like there are cost overruns. The permit for the transport of 100 MPa is needed. The question becomes how much more it would be to pay for this project, based on the results thus far.
- Perhaps a 95 MPa storage location under the compressor box could also be applied at stationary/permanent retail stations to reduce the footprint. This appears to be a design concept that is already implemented at compressed natural gas (CNG) stations to reduce the footprint needs (this may be something with which Bauer Compressors can help). The PI did not mention grounding, and it is unclear whether this will be a typical grounding rod, as installed by a general contractor/electrical contractor. It may be good to address this as part of logistics to site the AHMF; it is a requirement for existing 35 MPa mobile fuelers. It is unclear how the AHMF can be used to facilitate 70 MPa medium- and heavy-duty FCEV demonstration projects.
- The proposed future work plan will keep this project on schedule, yielding exactly what this project started out to do: build an advanced, fully functional mobile fueler. The project is compliant with the appropriate filling protocol (SAE J2601) and fuel quality (SAE 2719/ISO 14687). This system will undergo the same performance testing and qualification already established (i.e., the CSA Group's hydrogen dispenser testing apparatus and/or the NREL/California Air Resources Board's Hydrogen Station Equipment Performance [HyStEP] testing device).
- The future work is well-thought-out. It would be good to see a longer demonstration period.

Project strengths:

- The deliverable (i.e., mobile fueler) is based on existing stationary hydrogen fueling systems; mounting this on a flatbed trailer is excellent. The execution plan is excellent and should yield an excellent system on time. The team is very committed and dedicated to the success of this project. For example, the industrial partner on the team absorbed an increase in costing resulting from issues with the LN2 cooling system. The cost absorption kept the project moving forward in a timely manner without an increase in cost to DOE.
- This is a good team that is well capable of carrying out the project. This is a good solution to the barrier of fuel access in the early stage of the market. This project could enable potential users to "try before they buy." The project results would help potential users get comfortable with the technology while they plan for a fixed station.
- This is the first small station size 70 MPa mobile fueler that meets the SAE J2601 H70-T40 fueling protocol. A DOT special permit for 95 MPa efforts is also a strength. In addition, footprint reduction efforts provide fueling in a variety of locations with swift installation after permitting is completed.
- There is a need for refueling. The project is standards-based, and there is an interest in practical considerations (weight). The goal of data sharing is also a strength.

Project weaknesses:

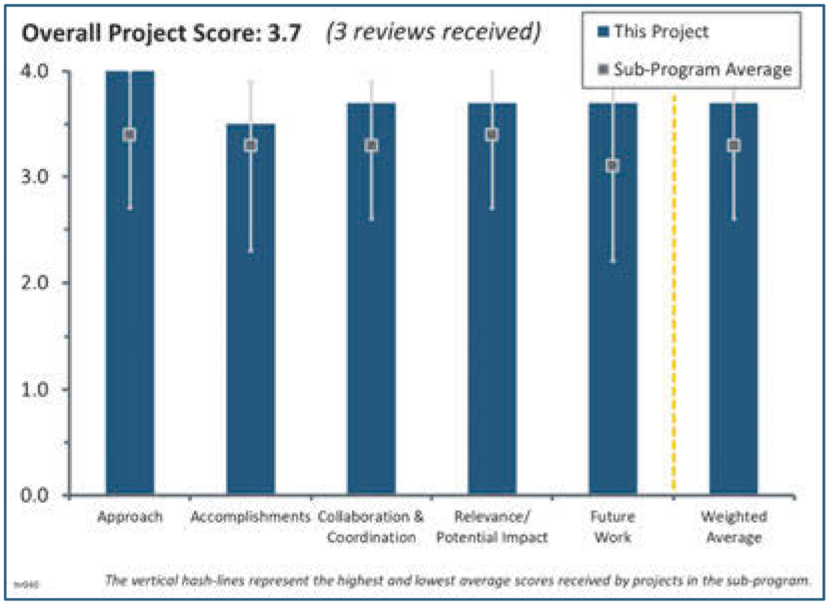
- It would be helpful for the PI to clarify for reviewers (as well as potential site hosts) how refueling of buffer storage occurs. In California, operation with a diesel generator may be challenging in 2020 (even for low emissions). Therefore, there is a need to emphasize capability for plug-in of a system. It is unclear how operating expenses are expected to compare to those of permanent retail stations.
- It would be good to see longer a demonstration period. It is unclear whether the system can be scaled up to supply fuel to larger vehicles. The team should consider using this for medium- and/or heavy-duty vehicles.
- Cost controls are needed, cost overrun is reported (verbally during the presentation), and there is no clear path for permitting,

Recommendations for additions/deletions to project scope:

- A roadmap to integrate with existing stations in the northeastern United States should be added. Permitting contacts are needed. Plans for maintenance were not verbally presented but most likely exist. Plans to keep the refueler at a site operated by one of the project partners were presented, but it is uncertain what the accessibility for others would be if the trailer were kept at this location. It is unclear what the fuel distribution plan is for the location mentioned.
- The team should consider transferability of "under compressor box 95 MPa storage" on the AHMF to permanent retail station designs that may help reduce the footprint (already practice for select CNG station providers).
- It would be good to have a longer demonstration period. The team could publish the experience from demonstration partners; this could include how well the station met the user expectations.

Project #TV-040: High-Temperature Electrolysis Test Stand

Richard Boardman; Idaho National Laboratory



Brief Summary of Project:

The project objective is to advance the state of the art of high-temperature electrolysis (HTE) technology by discovering, developing, improving, and testing thermal/electrical/control interfaces for highly responsive operations. The project will (1) develop an infrastructure to integrate support systems for 25–250 kW HTE testing units, (2) support HTE research and system integration studies, (3) measure cell stacks, performance, and materials health under transient and reversible operation, (4) characterize dynamic system behavior to validate transient process control models, (5) demonstrate integrated operation with co-located dynamic thermal energy distribution/storage systems, and (6) be operated with co-located digital real-time simulators for dynamic performance evaluation and hardware-in-the-loop simulations.

Question 1: Approach to performing the work

This project was rated **4.0** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach of developing a 25 kW test stand followed by a 250 kW unit is logical and reasonable.
- This project is focused on providing data to fill in information gaps in the implementation and demonstration of high-temperature electrolyzers. It is also noteworthy that the project is sizing the testing equipment to balance costs (smaller systems) and physical/commercial relevance (larger systems). There is a bit of concern as to whether the synthetic fuels portion of the project might distract from the more fundamental electrolyzer operation characterization. However, for the moment, it does not seem to be a severe impediment. It is also very good that this project is leveraging advancements made in the similar low-temperature electrolysis project and making the most of the resources there by implementing the same front-end controller developed in that project.
- The rationale for two reactor scales was well presented. A critical scale is required to be able to measure the relevant effects without unnecessary expense. Controller design is typically a critical component of a project like this and has appropriate focus to provide the most relevant information.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project appears to be progressing well, with a reasonable progression of scale in the equipment tested, and the first of those equipment-testing phases beginning soon. With a project horizon to 2020, this appears to be satisfactory progress. There was a mention that the project's continuation is determined annually through DOE consideration.

- The project appears to be on schedule for the 25 kW test unit. It is not clear about the plan for the 250 kW unit.
- The project is slightly behind but on a good track.

Question 3: Collaboration and coordination

This project was rated **3.7** for its collaboration and coordination with other institutions.

- The mix of collaborators seems thorough and appropriate. It was not entirely clear what the role of Exelon in the project was. This project appears to have many parallels with the similar low-temperature electrolysis project, in which partner Pacific Gas and Electric is helping with real-world grid operation data. It was not entirely clear whether Exelon was filling a similar role or only acting in an advisory role. Any amount of real-world data and operation information Exelon is able to support and provide should be enthusiastically pursued.
- Collaboration with each entity was described well. There was good interaction with other national laboratories, stack suppliers, and grid operators.
- It is not clear about the collaboration with suppliers/developers of HTEs.

Question 4: Relevance/potential impact

This project was rated **3.7** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is important in showing both technical feasibility for solid oxide electrolyzer cell technology, as well as improved technoeconomic data for market viability.
- It is critical to have reliable and versatile test units for HTE technology.
- While the project does meet overall DOE objectives and is a valuable project within its field, it is hard to see the higher-level initiative as mission-critical. With the recent history of the development of the energy industry, both domestically and internationally, it is difficult to see a future with a large nuclear power presence. This project may lead to some insights that could build better-informed cases for when and where the technology might fit in better than expected within most projections of the future energy market. However, at the moment, it is difficult to say with certainty that this will be mission-critical to the success of hydrogen as a fuel in the future.

Question 5: Proposed future work

This project was rated **3.7** for its proposed future work.

- Next steps for the project are clearly defined, and continued engagement with industrial advisors is planned.
- As with the overall approach for the project, the plans for future work are well ordered and logical.
- If “Support of the advancement of HTE stack technology....” is one of the objectives of this project, no plans and discussion of approaches were given in the presentation.

Project strengths:

- This project has good engagement with industry and fills a clear gap in the ability to test large prototypes for HTE.
- The strengths of the project are its likely relevance for the industry, the technology that is being demonstrated, and the way in which the project is intelligently leveraging complementary work completed in other projects.
- This project is logical and has a well-defined approach.

Project weaknesses:

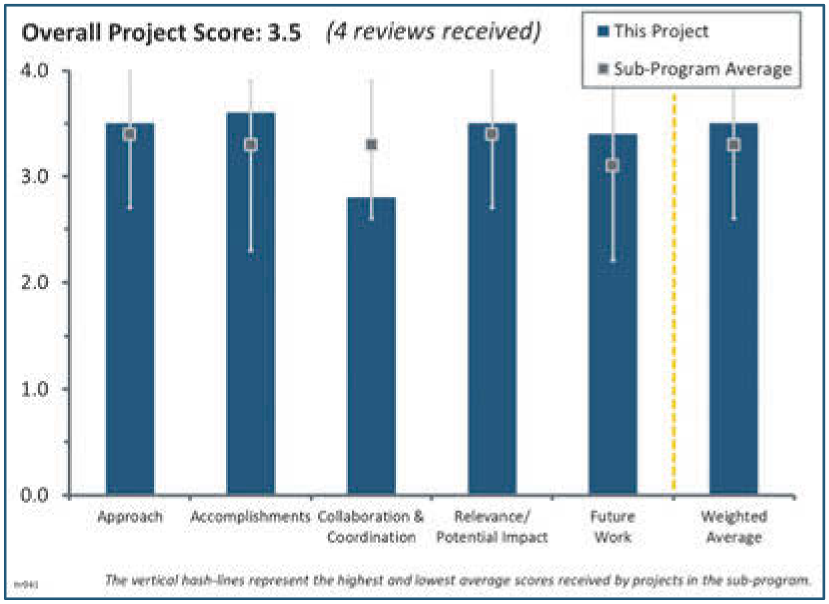
- No major weaknesses are noted for this project.
- The project's weakness is the uncertainty in the ultimate relevance of the technology in the developing energy market, especially given the latest trends. This does not mean the work should end; it just does not seem mission-critical.
- The project's weakness is that its scope is unclear.

Recommendations for additions/deletions to project scope:

- Since the project has already installed the synthetic fuel production skid, no change is recommended at this time. However, at an earlier stage of the project, the project might have narrowed the scope by not including this additional aspect.
- The project should have a better definition for the effort "Support the advancement of HTE stack technology for robust performance…"

Project #TV-041: Modular Solid Oxide Electrolyzer Cell System for Efficient Hydrogen Production at High Current Density

Hossein Ghezel-Ayagh; FuelCell Energy



Brief Summary of Project:

This project seeks to demonstrate the potential of solid oxide electrolysis cell (SOEC) systems to produce hydrogen at a cost less than $2 per kilogram, exclusive of delivery, compression, storage, and dispensing. Project activities aim to (1) improve SOEC performance to achieve greater than 95% stack electrical efficiency based on lower heating value of hydrogen, resulting in a significant reduction in cost of electricity use for electrolysis; (2) enhance SOEC stack endurance by reducing its degradation rate; (3) develop an SOEC system configuration to achieve greater than 75% overall (thermal and electric) efficiency; and (4) improve subsystem robustness for system operation compatible with intermittent renewable energy sources and their load profiles.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach of developing the single cell, stack, and then the overall system is very straightforward and appropriate.
- The approach is well designed and appropriate for this type of work.
- The approach is complete and very organized.
- The project seems to be more of a technology or product development project than a technology validation project. The technology development work is reasonably laid out. A technology validation project would have more on-line operating time, along with multiple stacks to conduct statistics. The slides stated that the approach was a “top-down” type of approach, but since the project starts with the cell and moves to the stack, it seems more like a bottom-up approach. Overall, the approach is appropriate for a technology development activity, not for a technology validation project. At minimum, the team should have had multiple stacks to do statistics.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project team has made excellent progress, considering the complexity of the work.
- The project is on track and is very well aligned. The team has made excellent progress.
- The cell and stack testing results are very positive, and the parametric studies are very interesting. The team did more testing than the milestones required and had some very interesting data. For the degradation mechanisms report on slide 10, it would have been interesting (1) to state where the Ni was going and (2) to

explain what the reaction layer forming in the anode was. Furthermore, the go/no-go data was not consistent with the cell and stack performance data. For example, on slides 9 and 10, the cells show degradation, and on slide 11, the stack shows degradation; yet when the project team reported the go/no-go, the cell showed no degradation. This test should be repeated to see whether the team can replicate the excellent performance. The stack should also be analyzed to see whether the team can determine why the result is so positive and how to replicate it. The robot assembly consists of very nice work and is a good accomplishment. It seems to be more part of a manufacturing development effort, rather than a technology validation effort. The system is designed to operate at 5 bar, which is a very good accomplishment. The assumption that 200°C waste heat will be available does not seem very realistic. For a chemical engineer, this waste heat could be used somewhere in the plant; a more reasonable assumption is 110°C–125°C waste heat.

- The team appears to have made very good progress in the past year. One helpful aspect for performance evaluation would be the establishment of a cell baseline performance, as a reference, on each of the data performance slides.

Question 3: Collaboration and coordination

This project was rated **2.8** for its collaboration and coordination with other institutions.

- Collaboration is an area of weakness in this project, which would be significantly strengthened if a third-party partner were involved in the technical evaluation, and especially in the technoeconomic analysis (TEA). The technology under development has the potential to change the market; therefore, it is important to have credible and independent verification of the performance and economics. With the addition of a third-party evaluation, this could be a top-tier project in the Hydrogen and Fuel Cells Program portfolio.
- The collaboration is not clear. It is unclear whether a wholly owned subsidiary counts as a collaborator, but that is up to DOE.
- There is not a lot of collaboration per se, as it is essentially one company, and the role of the National Energy Technology Laboratory (NETL) is indirect.
- The role of NETL in this project is unclear.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This technology has the potential to change the market in the hydrogen economy development. The project has the potential to meet DOE goals while also addressing power issues related to grid-generated hydrogen, providing a compelling alternative to natural-gas-to-hydrogen (via steam methane reforming), as used today.
- When successfully completed, the project should have significant impact on the advancement of high-temperature electrolysis technology.
- High-temperature electrolysis is definitely relevant to Fuel Cell Technologies Office goals.
- This work may certainly have some impact on the market (when scaled up), but it is a technology development project, not a technology validation project (as indicated by previous reviewers and agreed to by the project leads).

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The project seems to have addressed all barriers and is now working to address technical challenges.
- The proposed future work is relevant and appropriate.
- The prototype performance testing and the TEA of the overall system performance will be critical deliverables for the project and should be given the highest priority.

- The project team plans to test the stack over long periods. It would be nice multiple stacks could be tested so the team could calculate some statistics. The team members should see if they can replicate the very interesting results obtained from their current stacks.

Project strengths:

- This project has unique technology that leverages the natural-gas-to-hydrogen reforming method while producing power. This could be a significant game changer in the industry as we begin to reach the limits of renewable penetration in the grid and run into dollars-per-kilogram issues with electrolysis. Some regions of the country will have significant opportunities for this pathway.
- The project team is doing research on a very important area. The team has a good deal of experience, and the project itself is well funded and has demonstrated good durability.
- The project has a well designed and logical approach to addressing the technical barriers.
- This project is innovative and is moving along well.

Project weaknesses:

- The project does not have any partners other than a wholly owned subsidiary. Also, the researchers are not doing any statistics. This is especially important for the stack that was used for the go/no-go and showed interesting performance. The project team needs to figure out why the stack is performing as well as it is and replicate the performance.
- The project would be strengthened by independent evaluation of the TEA results. Many questions from reviewers on the technical validity of the results in the areas of energy integration and overall process efficiency could be addressed by the addition of a partner to complete/validate the results independently.
- Details on certain approaches (e.g., how to reduce performance degradation) are lacking.

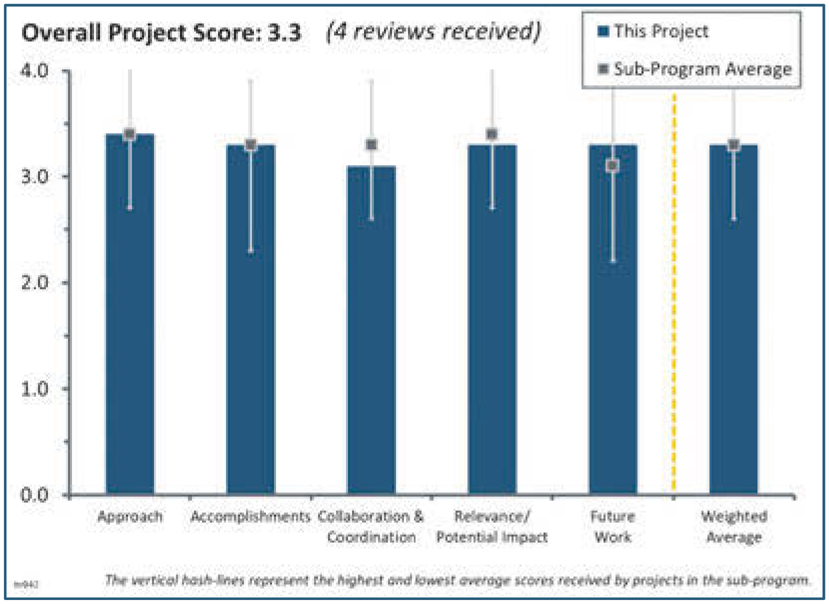
Recommendations for additions/deletions to project scope:

- The project team needs to do more technical evaluation (such as performance replication).
- It is recommended that the team define priorities and provide more details on future work.

Project #TV-042: Optimal Stationary Fuel Cell Integration and Control (Energy Dispatch Controller)

Genevieve Saur; National Renewable Energy Laboratory

Brief Summary of Project:



Current control strategies for building systems tend to be simplistic. The objective of this project is to create an open-source, novel energy dispatch controller to optimize the dispatch of different building components such as combined heat and power, storage, and renewable generation systems. Such a controller, which will incorporate improved forecasting capabilities and model predictive control strategies, would enable these building systems to participate in grid ancillary services markets. A planning tool for sizing building components utilizing simulated dispatch will also be developed.

Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project has a clear approach to working with multiple technologies, including fuel cells, to optimize cost and reduce energy use. The use of dynamic schedules is the right approach to find optimum building operation, reduce cost, and facilitate more renewable energy integration while saving money. The clear target of reducing fuel cell costs and operation shows the value of the work. The cross-functional approach is very valuable, given the integration of multiple disciplines across fuel cells, buildings, grid integration, and renewable energy production. The predictive control to help manage temperature setpoints with minimal intervention is critical to widespread uptake and not relying on steep learning curves from the occupants. The model structure is comprehensive and covers all the major energy consumption levers for reducing cost.
- The project approach is well aligned with the project goals.
- The approach is well designed and appropriate.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The effort to simplify the building and get to a reduced order model that is easier to integrate is an important first step to integrating and validating the model. Deep modeling of building dynamics and temperature of various subcomponents with different rates of heat transfer shows attention to detail and the challenge of optimizing multiple inputs. The co-simulation model used by industry should allow for easier implementation to the combined model and make it easier to explain how the model works, as industry already uses this model for managing energy use.
- The accomplishments of this project seem excellent; however, the communication of the actual accomplishments versus simply results makes evaluation challenging. This project seems to be

concentrating on the development of a model, which leaves the accomplishments lost in model details, rather than demonstration of the impact of the technology. The observer is left to infer too much from the results. It is also difficult to determine how the efforts to improve the model are accomplishments. It is not clear what issues were addressed or how the efforts improved the current state of the art.
- This project shows good progress, but it is unclear how the challenges of this complex issue will be addressed to meet the overall project and DOE goals.

Question 3: Collaboration and coordination

This project was rated **3.1** for its collaboration and coordination with other institutions.

- The project shows outstanding collaboration among various laboratories, universities, and industry. The cross-functional and cross-discipline effort requires clear goals and directions to meet project milestones and to validate the model. The extensive panel of collaborators and project advisors shows a well-rounded group required to get to comprehensive testing and evaluation.
- There is excellent coordination with other national laboratories. Improved interaction and collaboration with industries are necessary.
- The collaboration partners are all focused in research. The lack of clarity in results, the lack of focus in research, and the overall poor communication of efforts in this project seems attributable to the lack of diversity in the project partners. Dissenting opinions and relevance to industry for adoption of results are critical to strong project impacts; otherwise, the project becomes an interesting exercise with no net impact.

Question 4: Relevance/potential impact

This project was rated **3.3** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is quite relevant to DOE goals for saving energy and supporting the commercialization of fuel cells. The project has three clear impacts: grid modernization, building control, and fuel cell deployments. The efforts of this project are very relevant and, when validated, have the potential to save significant energy, considering building energy use is one of the top sectors of energy use.
- When successfully completed, this project will have a significant impact on the ways building energy is managed.
- This project could have a significant impact on the barriers it seeks to address. However, the lack of clarity in the information, the lack of focus, and the lack of diversity in collaborators significantly restrict the realization of this impact.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The next steps will be critical to playing out the value of the project. All the parts will come together and will have to be validated and integrated into an actual case study and application. The reduced order model will have to be finalized to the depth needed, followed by integration with the co-simulation model where testing is completed.
- The proposed future work is consistent with the project plan.
- The proposed future work is focused solely on continued levels of detail for the current effort. The researchers should consider efforts that improve the impact and relevance of the work and seek partners to help guide the future work, rather than just following the science to the next level of detail.

Project strengths:

- Building efficiency and integration of fuel cells has been demonstrated globally as a tremendous potential benefit. The use of grid modernization as a vehicle to promote and promulgate fuel cell technology into

building efficiency improvements has significant potential. Thus, this work has the potential for significant impact.
- The project's number one strength is the integrated nature of multiple disciplines and the bringing together of different expertise to solve energy consumption. Building management, fuel cells, and renewable energy can all be optimized only when each area has a tool, as developed through this project, that allows seamless real-time communication, or predictive modeling.
- The project has a well-designed and appropriate approach.

Project weaknesses:

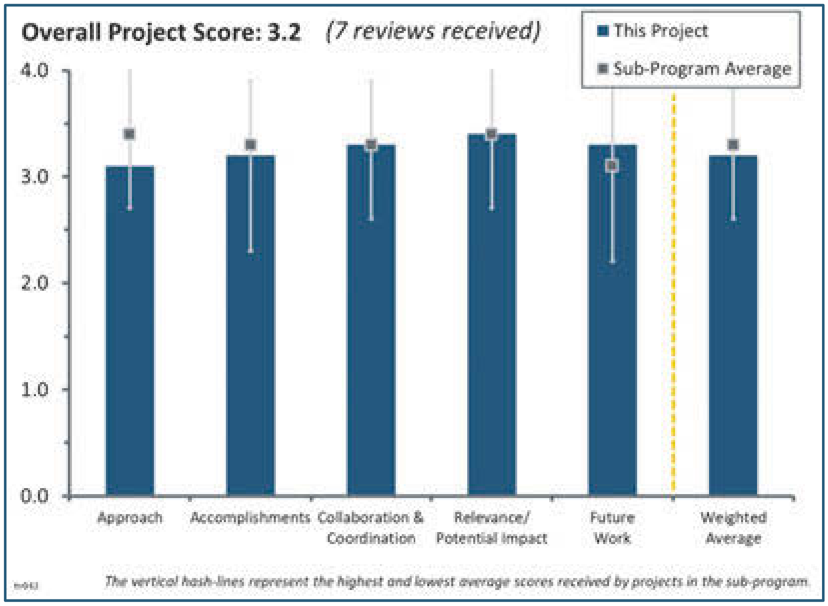
- The project's weakness is the challenge of relying on a third party to take source code and bring a viable commercial product to market that can actually be implemented outside of the laboratory resource framework and expertise.
- Despite the potential for significant impact, the project is not well positioned to provide that impact. It is not likely that this project will uncover a significantly unknown aspect of fuel cell integration or grid modernization benefit. The project is most beneficial in the demonstration of opportunities for these technologies. Thus, the project needs a stronger component of information promulgation and a better understanding of the barriers to technology implementation. It is unclear what the barriers are in the promulgation. It is also unclear what commercial partners need to understand from this research to realize the benefits. Lastly, it is unclear how this project can address those needs. A steering committee composed of commercial partners or workshops with commercial partners to determine the needs are both potential methods to realizing the project's potential.
- The project shows minimal interaction and collaboration with industry such as energy companies, building management companies, and architecture/building design firms.

Recommendations for additions/deletions to project scope:

- The team should add scope to support implementation of source code in preliminary hardware to allow the start on the pathway to commercialization on top of low-cost open-source hardware.
- More interaction/collaboration with energy management companies and architecture/design firms is recommended.

Project #TV-043: Integrated Systems Modeling of the Interactions between Stationary Hydrogen, Vehicle, and Grid Resources

Samveg Saxena; Lawrence Berkeley National Laboratory



Brief Summary of Project:

Hydrogen technologies offer the unique ability to simultaneously support the electricity and transportation sectors, but the value proposition for such systems remains unclear. This project is developing an integrated modeling capability to establish the available capacity, value, and impacts of interconnecting hydrogen infrastructure and fuel cell electric vehicles to the electric grid. The potential to support the grid and the potential to balance resources from flexible hydrogen systems, such as dispatchable production of hydrogen by electrolysis, are quantified. The project is also developing methods to optimize the system configuration and operating strategy for grid-integrated hydrogen systems.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach is good in couple of key ways: (1) it relies on existing (and presumably validated) models for many of the inputs, rather than attempting to recreate them, and (2) it is comprehensive in dealing with electrical inputs and vehicles needed.
- While this is nominally a Technology Validation (TV) project, in actuality it is a Systems Analysis (SA) project. Not surprisingly, the "barriers addressed" (slide 2) are not specifically included among the technical barriers cited in the TV section of the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP). This project does address selected barriers cited in the SA section of the MYRDDP. The hydrogen–vehicle–grid-integration model (H2VGI Model) utilizes and builds on a foundation provided by prior work on other models. The approach, as summarized in slides 5 through 8, seems comprehensive and impressive. While the cost is significant, and there is concern about overlap with other analysis and modeling efforts, as an SA project, the approach likely warrants an "Excellent," or even an "Outstanding." However, it is minimally responsive to TV objectives. Therefore, the compromise is an evaluation of the approach as "Good."
- This is a great approach to the effort of looking at integrated transportation and grid hydrogen production. There may be some challenges with bringing together so many models, with complicated assumptions, to reach transparent and "realistic" results.
- The team has made good use of real-world data (driving diaries and National Renewable Energy Laboratory [NREL] composite data products on refueling behavior) to input into the model. It would be good to see more information on what the "H_2 fueling station as a flexible load" profile looks like. It would be helpful to start with the U.S. Department of Energy target price for hydrogen and see whether the scenarios can be narrowed down to a few that look like they hold the most promise in achieving that target.
- The project is looking into the technical potential to flatten the duck curve using surplus electricity to make hydrogen and, in the H2G scenario (a reversible electrolyzer), to make hydrogen or supply electricity back

to the grid. This study goal is worthwhile. However, the approach does not seem to integrate cost into the picture. The duck curve seems to be exclusively for central electrolysis, yet the next slide indicates that distributed electrolysis is half the price. It is not clear whether the project also included distributed electrolysis in the duck curve analysis—and if not, why not.
- The approach of this project is appropriate and reasonable.
- The main issue (and reason for the grade assigned) is that much of the purpose of the project is to examine issues that industry can address, yet the two partners are national laboratories rather than industry. The project team will develop a model with little indication that the model data will be vetted well by suppliers and other industry.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Dr. Wei's presentation (slides 9 through 14) conveys a message that modeling results from the project have excellent potential to be beneficial for both government and industry stakeholders. Practical applications, and important questions, are helping to guide some complex and sophisticated modeling work. Without further study, this reviewer is not qualified to comment on the model's design, methodology, assumptions, inputs, etc.; however, the capabilities of the investigators and analysts at the national laboratories involved provide confidence in the results, including those highlighted and summarized in the presentation. Performance indicators for a project of this type are inherently not clear and measurable. Slide 8 perhaps comes closest to a statement against which to measure project accomplishments. Based on that statement of activities and questions, there has been excellent progress in achieving project objectives.
- The project has made good progress toward goals by showing preliminary cost numbers, even if the numbers were not entirely expected, with distributed generation's being lower-cost than centralized production. Sub-model development and integration has been completed within the expected time. Preliminary case study results have been peer-reviewed.
- The work being published in the *Journal of Power Sources* is very informative, and the publication will be the first time that utilities have concrete information with which to begin thinking about hydrogen as integrated with the grid.
- The accomplishments and progress of this work are very relevant, and the assumptions are clear.
- In slide 8, the main takeaway seems to be the limited benefit of electrolyzers for peak shaving (rather than the stated takeaway of the analysis being conducted for the first time). It is not clear whether the presenter was saying that the impact of electrolysis is significant or only modest/minor. The impact seems limited. The presenter's comparison of central vs. distributed was interesting and noteworthy. It supports analysis done many years ago (but presumably with undated assumptions). However, the assumptions are not clearly shown. While a comprehensive display of all assumptions is impractical, additional information should still be included (at least in the backup pages). On another note, the feedback gained from stakeholder outreach is excellent.
- The construction of the model, the use of real-world inputs so far, and the use of the webinars to gather stakeholder information are significant accomplishments. It would be good to see more sensitivity analysis of electrolyzer capital cost vs. capacity factor. It would be helpful to know what happens to costs if electricity is very cheap during the peak solar hours but the electrolyzers are run only at those times.
- While observations related to the study and inputs can be and were measured, it is not clear how the project itself can be measured, as clear and measurable performance indicators on the project do not appear evident. To that end, the lack of project assessment, rather than the inputs, is the project weakness.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The use of the stakeholder webinars is an exceptionally good way to validate the approach, inputs, and scenarios. It would be good to reach out to multiple utilities; several seem to be looking at grid support and the potential of dispatchable loads.

- The workshop with industry participants greatly improves the diversity of collaboration.
- This is a difficult analysis project, and the team seems to have coordinated with other institutions quite well.
- The partners on this project are all DOE national laboratories. Evidently there is no cost share; DOE is paying 100%. The TV section of the MYRDDP states that projects are 50–50 cost-shared between the government and industry. On the positive side, project managers conducted two webinars, during which representatives from industry, academia, and government provided feedback and inputs. In response to a question, Dr. Wei indicated that project managers recognize the importance of sharing results with, and receiving inputs from, potential stakeholders. Project managers from the three laboratories involved are collaborating well on integrating the models and related activities that are important for this project's success.
- The grade assigned was a compromise, as the two partners undoubtedly worked closely with each other (supporting a higher grade), but there is little indication that the two partners worked sufficiently with others (therefore calling for a lower grade). While support from the Hawaii Natural Energy Institute (HNEI) is documented, little information is provided about who the other twenty or so webinar participants were or what the participants from industry, academia, private research (not defined), and government provided. Worse, there was a total of two webinars, and except for the support from HNEI, it is unclear what other additional collaboration existed for the $1.65 million effort beyond the work of the two laboratories.
- There is coordination of multiple laboratories as a result of so many models being integrated and used for inputs. The project could use additional industry or regulator input to ensure adoption outside of modeling efforts.
- The project should keep involving industry, especially the Electric Power Research Institute and utilities.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Because this is a difficult topic to analyze, systematic analysis has been limited. Better understanding of how various modes of production can integrate with grid demands is key to successful hydrogen implementation. Thus, this project is relevant and will have a significant positive impact.
- This project strikes at the heart of the discussion in California and is appropriately scoped to evaluate that early market. This project has significant relevance and potential impact.
- As summarized in the presentation (slides 3 and 4), this project is clearly relevant in the context of better understanding the potential for hydrogen and fuel cell systems. While not particularly relevant for TV objectives, the results promised by this modeling project should certainly help achieve FCTO's SA objectives. If realized, the objectives stated on slide 3 will provide valuable inputs for decisions by both public- and private-sector stakeholders.
- The project certainly supports some goals of the Hydrogen and Fuel Cells Program but recognizes that a greater need may exist to develop research for product advancements that promote the use of fuel cells.
- A utility company like Southern will be very interested in these results and methodologies.
- Grid integration and support using electrolysis as dispatchable loads is a key element of H2@Scale. The analysis needs to expand beyond just vehicle hydrogen fueling stations and include other value-added uses of hydrogen.
- Specific case studies could be more targeted to real-world problems to somewhat validate initial results. The integrated approach could have significant impact if adopted in the future.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The remaining challenges and proposed future work, summarized on presentation slides 17 and 18, seem logical and reasonable. Applying the model and related analysis to "real-world" conditions and scenarios, e.g., those associated with utility regions in the Western interconnect, is a good plan.
- Future work to explore liquid hydrogen delivery will be important to starting to match or calibrate results to current industry experience. It will be interesting to see more Plexos integration and industry input to help validate results.
- Future work is reasonable, although it seems like more could be done with the model beyond what is proposed.
- The future work is in line with the plans.
- Sensitivity studies related to different hydrogen usages and to different capacity factors would add value to the project.
- This project should find an answer that resolves the questions of why station providers are not realizing the significant benefits demonstrated by this work, what the gap is, and what will help address this gap. Improvements to the models and promulgation of the results are interesting, but there are real-world examples either deployed or in development that could inform a discussion around these key questions.
- Before a decision is made about additional work, it might be worthwhile to ensure that the money would not be better spent elsewhere.

Project strengths:

- Project strengths include the modeling and analytical expertise available in the three national laboratory project partners: Lawrence Berkeley National Laboratory, NREL, and Idaho National Laboratory (INL). The H2VGI Model utilizes and integrates the results of previously developed models and analyses. Results of the work are beginning to be applied to actual power generation and transportation scenarios and to be used to answer questions related to the future of hydrogen and fuel cell technologies. The project has significant relevance in the context of overall FCTO objectives.
- The team has pursued an ambitious analysis project that entails a wide breadth of geographic and production scales. The approach is logically constructed and explained. The team appears to be well balanced for the work needed.
- The project provides a good overview and tools for assessing the value of grid support services in conjunction with vehicle hydrogen fueling to reduce the cost of fuel. The project can be strengthened by considering other uses for the hydrogen produced and by including sensitivity studies where appropriate to gauge the effects of varying different parameters.
- The project is well aligned with important issues in a very critical early market.
- The project is comprehensive and builds on existing science.
- There is strong laboratory integration across multiple models from NREL, and collaboration with INL.
- Laboratory data are plentiful and well organized.

Project weaknesses:

- Additional assumption details need to be included to assess the reasonableness of the results. The cost difference between central and distributed is substantial, but the cost analysis seems to be divorced from the other aspects of the project. Conclusions as to the cost impact on the system are not discussed. The project is a substantial investment ($1.6 million), yet the results are that electrolysis has only a limited impact on flattening the duck curve. It seems that modeling apparatus could be used for other studies, beyond those listed in future work. Finally, the future work activities do not seem that interesting or likely to have a large impact.
- The stakeholder webinars cited in the presentation are a positive step. However, the project managers should increase the focus on, and intensity of, collaborations with organizations having an interest in H2VGI modeling results. Assuming funds are available, workshops should be planned to (1) present the

model's capabilities and results, e.g., case studies; (2) receive feedback on methodology, assumptions, etc.; and (3) ensure agreement regarding model priorities and questions to be addressed.

- Beyond the coordination between NREL and INL, there appears to be minimal collaboration with outside activities. Outside collaboration appears to be limited to data from HNEI and two webinars consisting of about twenty people per seminar, of which about half were from industry, academia, and government activities—indicating that about half the webinar attendees were from one of the laboratories. Also, the pressing need for this project is unclear.
- This is a large project that has many assumptions built into the various models. Continuing to validate the assumptions and identifying/understanding the discontinuities/inflection points in the results will be challenges.
- The results are inconsistent with industry experience and industry opinion. The project needs to find out why that is the case and identify the barriers.
- It would helpful to connect this project to TV-031 and to demonstrate that the benefits ascribed are possible with control systems that have been identified and validated.
- The project is overly reliant on laboratory modeling that is coupled without intermediate validation.

Recommendations for additions/deletions to project scope:

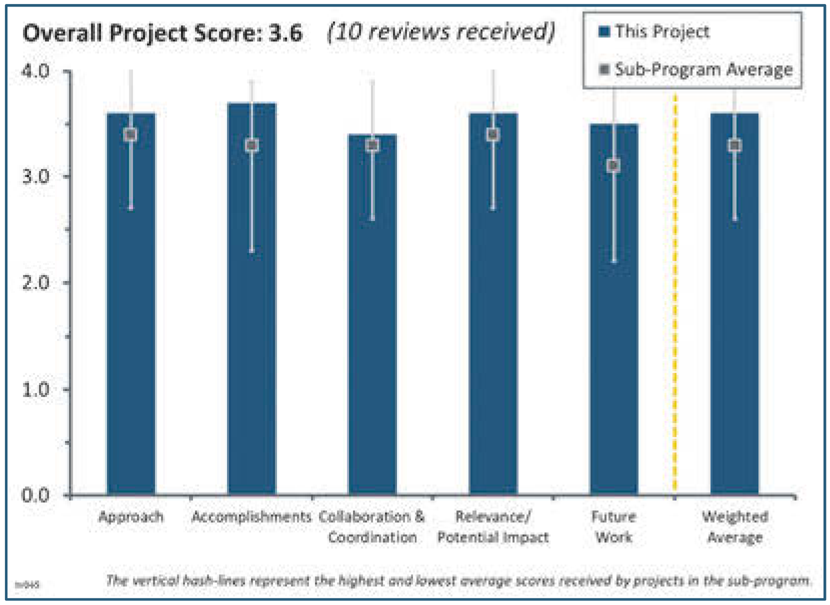
- The hydrogen refueling amount in slide 7 is curious; inquiry should be made as to why so many people refill only 1–2 kg at a refueling. Future work tasks should be increased to make better use of the model. Additional assumptions should be included in future presentations (specifically related to the cost analysis—some of the electrical usage values between central and distributed are surprising and not explained). The question of whether central vs. distributed has any effect on the shape of the duck curve should be analyzed.
- The results of this project have good potential to assist in making decisions relating to investment of private and public funds. However, with limited funds available for analysis, FCTO's SA team should continually ensure that this project is not duplicating or overlapping other modeling and analysis work being funded by FCTO and other organizations.
- The project should undertake additional case studies and validation of potential for forecasting cost and demand by region or hydrogen vehicle placements.
- While the discussion of using an H2G two-way fuel cell to reduce the power peak is interesting, the technology may not be technically feasible at this time. While the discussion might inform decisions as to whether to focus resources on developing such hardware, it is not likely useful for near-term design and investment decisions, as no efficient large-scale equipment that can do that exists, and the round-trip efficiency of grid–hydrogen–grid is poor.
- The recommendation is to minimize this project in favor of industry research.

Project #TV-045: H2@Scale Analysis

Mark Ruth; National Renewable Energy Laboratory

Brief Summary of Project:

H2@Scale is a concept that explores the potential for wide-scale hydrogen production and utilization in multiple energy sectors in the United States. The objective of this project is to improve the fidelity of the H2@Scale value proposition. The analysis seeks to quantify the potential economic, resource, and emissions impacts from wide-scale hydrogen production and utilization. In addition to conducting nationwide analysis, the project will also identify regional opportunities and challenges. H2@Scale analysis integrates many transportation, industrial, and electrical sector analyses and tools.



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project has a solid connection with the DOE goals and objectives for H2@Scale. This effort gives perspective to the project's significance. The speaker noted some of the material presented is "already outdated," and this is a realistic perspective, to a point. Some of the supporting data may be "dated," but the approach(es) to performing the work can be used for a long time. The approach started with the relevance of the project: analysis makes the projection of light-duty vehicle penetration (with low-cost renewables including electricity). The analysis hinges on the economic potential of the H2@Scale concept, overall. Findings are based on resource potential (resource requirements): geographic locations and markets, and real-world performance. The project team compared to last year's efforts, which focused on economic potential. The team started with market sizes, first for industrial markets (existing markets, but opportunity costs were not explained); electricity markets (which are much like natural gas—flexible, although the team did not explain this); and transportation markets (seven-year-old National Research Council [NRC] reports were used) (this study should be blended with others and not used alone). The project team explained how the electricity source can be replaced with hydrogen. The technical potential was defined (although for transportation, it was based on an outdated NRC study). It is recommended that the project update this study, then the economic potential. The overall approach is excellent.
- It is encouraging to see the U.S. Department of Energy (DOE) making these efforts to understand the underlying economics of the hydrogen supply chain through modeling of supply- and demand-side pressures. With this body of work, a common methodology for these economic evaluations can be made. From an industry perspective, this is an important step for DOE as it enables industry engagement without relying on proprietary industry market analysis and without the concerns of market influence based on such proprietary evaluations.
- The approach taken on this project is very robust in the way that it is not only relying on transportation models and tools but also integrating these with models associated with the industrial and electrical sectors that are essential for the H2@Scale concept realization. The parameters being provided for the technical and economic potentials are well aligned with the overall goal of this analysis work.

- Overall, the approach appears to be strong, and the results are well presented and cover the major areas of interest. This is a nationwide, economy-wide piece of analysis, so there are inherently many assumptions and choices that need to be made. The analysis seems to be reasonable in its assumptions, which of course can always be probed in more detail or shifted.
- The approach is well explained. The project makes use of existing analysis tools that have already been vetted. The differentiation between technical and economic potential is key to this project's approach. The demand–supply curve evaluation is ambitious.
- The project team presented thorough coverage of analysis for support of the H2@Scale concept and use of all DOE tools. The project addresses a key need in explaining and supporting technical and economic benefits.
- This is a very ambitious project with much input and many variables. The communication across all sectors is key. To the extent possible, the project team should keep a finger on what is happening in the "real world," i.e., what industry is doing and how the actual market is playing out.
- The approach used is stepwise, logical, and comprehensive. The approach first understands what is possible, then reduces it to economic considerations.
- This project is an excellent analysis on a very important assessment.
- Establishing the scenarios of future demand and supply for hydrogen that goes beyond transportation is a positive step. However, after finding the economic equilibrium price, there is no mention as to whether this price is economically feasible, given current technology. These curves should point out which industries and applications would be able to deliver hydrogen at the equilibrium price and which ones would be willing to pay that price. Also, it is not clear whether the hydrogen supplied includes transportation and distribution to the final user.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project used a wide range of situations in the United States, an overall DOE goal. The project included examples from the San Francisco Bay Area and rural United States (Appalachia), with an emphasis on electrolysis. The project made a good connection with the target price point of hydrogen dispensed and moved to "beyond the target" price. That price was a little too high: $3.00 for the hydrogen price for the demand curves. However, it was explained that this is the amount that needed to be paid. The project team reviewed the different ways hydrogen is produced—curtailed electricity, nuclear, and steam methane reforming (SMR)—and gave various values in the sectors.
- This project has a good analysis of hydrogen demand across sectors across the geography that was presented. The project team completed a broad range of scenarios that were analyzed for hydrogen economics. This gives a more fair comparison of what cost renewable hydrogen has to meet to be competitive.
- The project team has done excellent work on the accomplishments and progress shown on this work this year. The development of the demand and supply curves was key to understanding the potential economic potential of the H2@Scale concept, which now provides a more complete picture by building on last year's results on the technical potential.
- The analysis clearly made progress toward answering the key questions articulated at the start of the presentation. Assumptions are inherent in this type of analysis, but progress was definitely made.
- This project has made very good progress going from technical potential to economic potential.
- The depth of evaluations made in this project is impressive.
- This project is in full alignment with DOE goals.
- This project has made good progress; the development of supply and demand curves for four different scenarios is significant. It would have been good to see an actual case study or the initiation of an actual project as well.
- The integration of geographic analysis and market potential is very good. It is not clear how the technical potential demand was calculated. It was also unclear in what year the demand was calculated.
- In slide 10, the project team should provide the actual link to the data source, as one cannot readily find it on Google or the National Renewable Energy Laboratory's (NREL's) site. It would be nice to understand

how/where the assumptions were derived (e.g., light-duty-vehicle transportation). While the technical potential of renewable hydrogen from photovoltaics or wind for every county in the country is perhaps interesting, it is not very helpful if it does not consider any economics or realistic scenarios. Policy is a very important factor in all of this, and the project team should take this into consideration.

Question 3: Collaboration and coordination

This project was rated **3.4** for its collaboration and coordination with other institutions.

- One of the main strengths of this project is the expertise provided by world-recognized analysts, all of them from different entities, working as a very strong team. It is great to see that there is also feedback provided by DOE's Office of Nuclear Energy.
- The project team demonstrates good coordination with DOE national laboratories and mentioned a need for the example business cases. It seems likely that the private sector will want to collaborate with this project, since it is comprehensive and relevant. The project team mentioned technology transfer, but specifics are needed here.
- The laboratories appear to have stitched together their various analyses in reasonable ways and have worked together well.
- This project is very well integrated with several DOE laboratories.
- This reviewer looks forward to offering comment on the forthcoming report.
- The team needs additional collaboration with industry and government to initiate a project that can validate H2@Scale. It is encouraging to see that the team is partnering with the state of Texas to conduct a case study. The team is encouraged to look also at California, where the project would be more likely to get financial support for projects.
- The industry input may be a bit light. With all of the hydrogen activity in California and the Northeast, it is possible that getting input can be a challenge for the project.
- The project team did not explain the interactions with collaborators. Workshops have been held around H2@Scale to provide input, but it is not clear what mechanisms are being used in between to obtain industry input.
- This project has interesting preliminary results that are generally described clearly. The "hydrogen price" needs to be clarified as a production-only price. The project team concludes that if natural gas prices are low, only SMR will be used to supply hydrogen; but if natural gas prices are high, then SMR plays only a modest role, and electrolytic hydrogen generation is dominant. Plus, the price of electrolytic hydrogen must be about \$1.5–\$1.75/kg. However, assumptions as to whether and when electrolytic hydrogen can reach those cost levels are not shown.
- The project team could potentially improve the approach to validation in the market. It is unclear how, for example, the market predictions will be evaluated against actual costs that are seen in the field. Again, it is not clear whether there will be a long-term owner of these models who will have the responsibility to maintain and improve them as economic data is gathered and compared. It is not evident who this long-term owner would be (industry, trade organizations, DOE, etc.). The team should provide clarity about who will own/use these models in the future and how that will become part of industry reporting, as it is an important aspect of this project. The project could be strengthened by having the long-term owner of the tools/data/reporting on the team.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Past studies have examined individual aspects, but this project pulls them together into a combined assessment firmly set in an economic supply-and-demand framework. The project provides very relevant analysis that will explain/validate whether the hydrogen economy/H2@Scale concept is feasible.
- The project gave realistic scenarios of hydrogen production and the varied the price of natural gas, both base case and upper bound. This is good, for the increased demand for hydrogen in California shows a need

to keep planning for the upper bound. The project supports pipelines to bring hydrogen to the coasts (forward-thinking).
- This level of analysis is hugely important at this time when hydrogen is at a tipping point internationally. While it is good to look at an electrolyzer cost that can make the cases competitive, it is also important to provide a case more representative of today's technology.
- This project is in line with the [former] Market Transformation sub-program; the project is enabling and accelerating expansion of hydrogen and fuel cell system use by lowering the life-cycle costs of hydrogen and fuel cell power and by identifying and reducing the barriers impeding full technology commercialization. The work presented in the slides, together with the projects that DOE has selected to demonstrate hydrogen integration, is an important step toward lowering hydrogen costs using existing resources.
- This analysis is of extreme importance for a clear picture of the potential and impact of the H2@Scale concept. Understanding both the technical and economic potentials is definitely key to assessing the hydrogen implications beyond the transportation sector, which has been the main focus over the last several years.
- This project is very much aligned with the research and development R&D goals, and the potential impact of the results is significant.
- This is clearly critical to the overall mission of the Fuel Cell Technologies Office, and the results will contribute to future R&D efforts and setting R&D targets.
- This project is fully aligned with DOE goals.
- This type of analysis will really help in thinking about the future. In a subsequent project, it would be good to look at hydrogen technical/economic potential in terms of scale required to make an impact on the grid (such as the ongoing Lawrence Berkeley National Laboratory [LBNL] study by Dr. Saxena).
- The biggest concern with this project is that the project team does not consider the effects of policies on the markets. While DOE cannot advocate for policies or policy outcomes, it is imperative to understand how policies will affect the supply and demand sides of these evaluations. Particularly in early market stages, it is policies, not free market drivers, that will establish the supply and demand curves and their evolution in time. It is irresponsible for DOE to take the position that an economic market study will be completed without taking the effects of policies into consideration. It is unclear how one could make good policy decisions if there are no economic models that can show the effects on markets. A secondary concern is the accessibility of these models to users outside of DOE. It is unclear what access will be made to the tools being developed and how that can be best bridged to potential users in industry or markets.

Question 5: Proposed future work

This project was rated **3.5** for its proposed future work.

- The remaining challenges and barriers have been clearly presented, and the project team has clearly identified the necessary future analyses to address these challenges.
- The project's completion is moving forward as planned, and the ongoing updates are desirable.
- A qualitative analysis of a Texas transition plan would have some benefit, but a quantitative analysis would be better. Doing a Texas-only study might be good in that it is smaller than a national study and may better identify pros and cons of the approach.
- It is important to conduct a regional analysis to determine appropriate strategies for each area.
- The future work should also include more opportunity for industry input—webinars, surveys, etc.
- The presenter mentioned the need for more funding to support "deeper research." It is unclear whether the presenter can work with the concept of just-in-time production and distribution of hydrogen so that the fuel is where it is needed and the increased "real" access leads to price-at-the-pump decreases. It is unclear what the presenter's best-case scenario, or utopia, in the future would be. While the presenter has many answers and has already broke things down and studied them intensely, presenting his idea of the utopian scenario, market sensitivities, and the results would be appreciated and respected.
- The project should integrate overcapacity of either electricity or hydrogen production with a hydrogen refueling station or something similar. The logical next step is coordinating with government and/or industry to prove the models.

- The project team should continue to refine this work and narrow toward economic feasibility, as well as narrow the scope to specific regions.
- The continued use of these models in evaluating the various case studies banding the range of hydrogen market penetration is recommended, and the time when researchers can compare actual market data to the model predictions is happily anticipated. When at this stage, the tools will have real market value by giving stakeholders a common reference for these economic factors.
- The project is over, as the presentation said that there is no funding in fiscal year 2018.

Project strengths:

- Fundamentally, H2@Scale is a version of the "hydrogen economy" idea, and this analysis does a nice job quantifying, at the scale of the U.S. economy, the generation sources and uses for hydrogen across sectors. The supply and demand curves are important, even though there are plenty of assumptions, and provide a clear basis to assess research goals and understand when hydrogen could start to win on economics alone, for particular applications. The presentation was clearly put together and did a nice job of communicating results. A number of major questions that would be interesting to look at in future work follow:
    - It looks like hydrogen from nuclear will not happen, because the price per kilowatt-hour for current nuclear is just much too high. If this is correct, it could be stated in a more transparent way.
    - It is unclear whether it is realistic to build the types of hydrogen pipelines shown. There are lessons from the natural gas pipeline industry that could be applied. It is also unclear whether it is reasonable to permit and finance the types of pipelines shown. It would be good to know how big that investment would be compared to the annual build of natural gas pipelines today.
    - The assumptions and analysis that led to 28 MMT/y of hydrogen for storage were not clear. It would be helpful if the project team explained that in more detail, likely through a publication.
    - More information on electricity supply would be helpful. Presumably, curtailed electrons are free, and the rest of the electricity is bought at the denoted wholesale prices.
- The project's breadth and scope are huge. The resulting potential impact and value of the project are similarly large. The opportunity for presenting very compelling graphics based on the data generated is very high. As a word of caution, however, there have already been discussions in which the figure on slide 20 is interpreted as DOE's prediction for where hydrogen pipelines will be needed.
- This is a large, complicated undertaking that the NREL team appears to be handling in a methodical, clearly stated manner. The use of supply and demand curves is an excellent approach.
- This project has a highly complex set of data that the team explained well in the slides and orally. The analysis provides valuable data to support H2@Scale rationale and strategies for deployment. There is a good deal of data here that could be leveraged.
- The project is founded in solid approaches, including assumptions. The team presented clearly, with a passionate speaker, a strong presentation, and a broad approach. The project is providing needed work and needed results and insights.
- Overall, there is an abundance of "brain power" and information associated with this project, and there can be some information impactful to the industry.
- Starting from what is possible and narrowing to what is feasible is a strength of this project.
- This project has an excellent evaluation that should be completed as planned and, in the future, updated and further expanded as needed.
- The project team has strong technical knowledge. Data availability is a project strength.
- This team has strong modeling capabilities.

Project weaknesses:

- There are no evident weaknesses.
- The project just needs a scenario for utopia. It is already there, but it needs to be brought forward.
- In an analysis like this, there are always many assumptions to target, but it is clear that the team could vary assumptions, and the team clearly understands the different scenarios and can present on them as requested.

- Given the complex nature of the analysis, it is difficult to clearly explain the assumptions that go into the analysis. It is not clear that the team's planned reporting will have all the detailed assumptions necessary to challenge the analysis results. The creation methods (and details) of the supply and demand curves are not clear. Without confidence in those curves, the results are meaningless. There is no sensitivity analysis to assess the extent of change in the results due to changes in the critical assumptions. There is no identification of the critical assumptions or drivers.
- The underlying assumptions will be a challenge for this project. Another challenge is ensuring the economic analysis adequately captures the risk mitigation costs of industrial/utility investments.
- The likelihood of availability of hydrogen overcapacity is unknown, and the team did not assess the significant shift in the demand–supply curves. Also, the project lacks involvement of stakeholders that can build out infrastructure/initiate H2@Scale projects.
- The models do not consider the effects of policies on outcomes. This is a critical, if not fatal, weakness in the models in the early market stages when policies are much more likely to drive behaviors, prices, and market directions than in the open supply–demand curve modeling used here.
- The project team needs to keep in mind the policy comment as it affects the numbers and the "believability."
- The collaborations and follow-up with industry could be more thoroughly described.

Recommendations for additions/deletions to project scope:

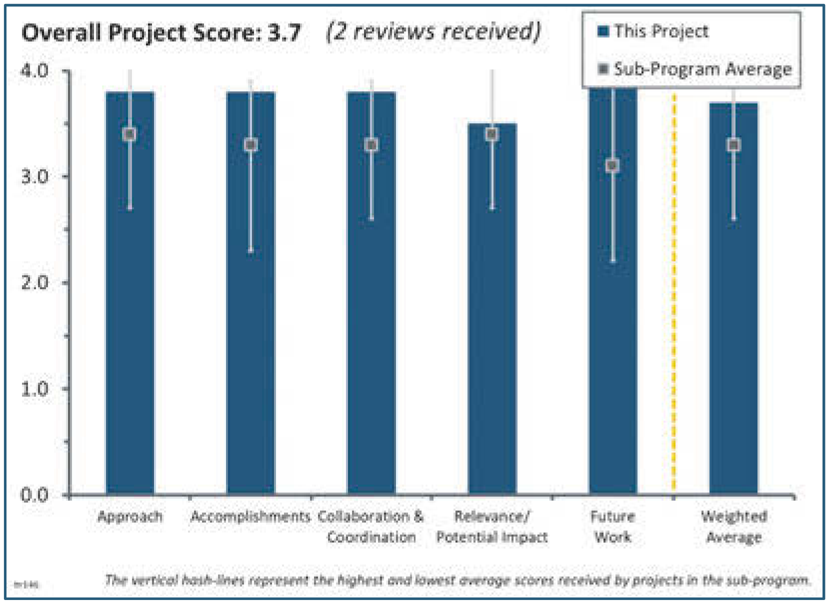
- This is a very valuable and potentially marquee project for the H2@Scale effort.
- The proposed future work will provide significant information.
- This project is over, but a number of additional scenarios could be assessed. The practicality (permitting) and economics of building a huge hydrogen pipeline system is of particular interest.
- The project needs a sensitivity analysis. The dollars-per-kilogram from electrolysis seems optimistic. It would be of interest to understand the team's exploration of how the supply curve changes with an increase. Also, the team should identify critical assumptions and analysis drivers. The project needs details and complete documentation of assumptions and a better description of how the supply and demand curves are generated.
- Connecting the dots between this analysis and R&D needs and impacts is critical for continuing; such an effort is needed to quantify how much technology advancements could reduce the cost of hydrogen and manage the gap to natural gas. It is important to analyze how policy also affects these models, while not endorsing any particular policy.
- The team should involve government and other stakeholders that can build out infrastructure and integrate demand and supply of hydrogen; initiate case studies and on-the-ground projects; assess whether it is cheaper to build high-voltage direct current (DC) lines to deliver electricity from the wind belt to the east and west coasts, or to build hydrogen pipelines to transport hydrogen from the middle of the country to demand centers; and assess potential shifts in demand and supply curves.
- The team should consider helping some of the other zero-emission-vehicle states, such as Oregon.
- The project team should add best-case scenarios.
- The team needs to periodically update on this project.

Project #TV-146: H2@Scale: Experimental Characterization of Durability of Advanced Electrolyzer Concepts in Dynamic Loading

Shaun Alia; National Renewable Energy Laboratory

Brief Summary of Project:

This project aims to evaluate electrolyzer durability with dynamic loading and assesses the ability of electrolysis-based hydrogen production to be cost-competitive while maintaining performance with extended operation. Los Alamos National Laboratory (LANL) will support the National Renewable Energy Laboratory (NREL) in (1) establishing baseline performance as a guide to catalyst/electrode development and (2) evaluating the influence of low loading, intermittency, and system controls on durability.



Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This project addresses technical barriers cited in the Fuel Cell Technologies Office (FCTO) Multi-Year Research, Development, and Demonstration Plan (MYRDDP). In particular, relevant barriers include barrier G, Hydrogen from Renewable Sources, in the MYRDDP Technology Validation (TV) section, and barrier F, Capital Cost, in the Production section. Project objectives are clearly stated. The project approach is well developed and logical. Electrode materials are fabricated, tested, and characterized at NREL and LANL.
- The project approach is good and described well by the principal investigator (PI). It is clear that the team understands the project goals and how the results will have relevance and impact.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Slides 7 through 15 provide evidence of significant activity and results since the project began on October 1, 2017. During the relatively short life of the project to date, the impacts of multiple variables on membrane electrode assembly performance and durability have been measured and quantified. These variables include iridium and iridium oxide loading, intermittency, wave type, ramp rate, and water quality. Materials characterization of single-cell test samples, using microscopy and X-ray diffraction, provides detailed information on metrics such as catalyst layer thickness, porosity, and equivalent diameter of pores. Selected results of microscopic studies show the impact on membrane durability due to changing test conditions. There has been outstanding progress in achieving project objectives. To date, the iridium and iridium oxide catalyst materials have been tested. The PI noted that no conclusions regarding “bigger-picture” issues can be drawn yet in regard to the implications of results so far for overall electrolyzer performance and cost.

- Not only are the accomplishments founded in strong science, but the results are well described. The presentation of the information is easy to understand, and the direct relevance is clear. The project evolution is easy to follow, and it is clear why the research work is following its current path and what impact the results have on the overall objective.

Question 3: Collaboration and coordination

This project was rated **3.8** for its collaboration and coordination with other institutions.

- This project is being carried out through a partnership between NREL and LANL. The responsibilities of each partner are clearly defined. Each week, single-cell MEAs, which have been tested at NREL, are sent to LANL for analysis and characterization. The presentation does not address or clarify how this project coordinates with other H_2@Scale projects, initiatives, and activities.
- The research has just started, but it is clear that there is a strong link from the research to the potential users of the information. The project should seek to maintain this level of collaboration as it proceeds.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is very relevant, and how the research will achieve an impact is clearly demonstrated.
- The relevance section of the presentation relates more to the overall H_2@Scale program, and water electrolysis hydrogen production, than to this specific project. The project being reviewed is evidently considered an element of H_2@Scale. The project's scope is limited. While it is hoped that results will inform electrolyzer design, materials selection, and operation, the project will likely contribute to cost-competitive hydrogen production only when combined with other, more robust development and testing projects.

Question 5: Proposed future work

This project was rated **4.0** for its proposed future work.

- Future work would build on the foundation established during the initial year of the project. The work described is a logical next step. The activities proposed should result in information that is beneficial for designers, developers, producers, and operators of equipment for hydrogen production by electrolysis.
- The project's future work should include the communication and collaboration efforts, not just the research tasks.

Project strengths:

- NREL and LANL investigators have been productive. Results and information produced to date have been plentiful and detailed. NREL and LANL have state-of-the-art testing and diagnostic capabilities/equipment. Project objectives are clearly stated, and the approach to achieving them is logical.
- This project is well focused and well communicated.

Project weaknesses:

- The project could fall into a common trap in which the research efforts are the only focus. The project team should ensure that an increased amount of effort is spent on communicating results to both the academic and commercial communities.
- The project's scope is limited. The project scope will likely contribute to cost-competitive hydrogen production only when combined with other, more robust development and testing projects.

Recommendations for additions/deletions to project scope:

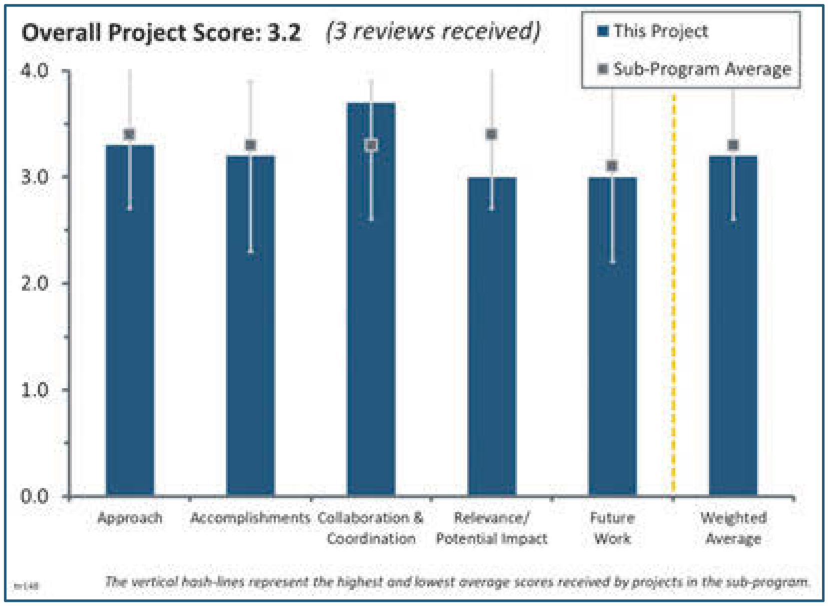
- Presumably, project continuation beyond the first year is dependent on additional funding of about $400,000 annually. Therefore, it can be assumed that continuing for another year is warranted and reasonable. After that, however, a critical assessment should be done to determine the probability that results achieved will contribute substantively to FCTO's goals of improving hydrogen production performance and lowering costs. How well this project is integrated and coordinated with other activities (e.g., other H_2@Scale projects) should also be factored into the continuation decision. It is recommended that the presentation at next year's Annual Merit Review should address this issue.

Project #TV-148: Hydrogen Stations for Urban Sites

Brian Ehrhart; National Renewable Energy Laboratory/Sandia National Laboratories

Brief Summary of Project:

The primary objective for this project is to create compact risk-informed and performance-based liquid hydrogen reference station designs that are appropriate for urban locations and permit hazard reductions, as well as improve near-term technology. Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST), a Sandia National Laboratories–National Renewable Energy Laboratory collaborative project, will partner with industry stakeholders to identify methods of reducing physical station footprints and address the possibilities for station layouts within urban sites.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach is clear, and the relevance of the information is well understood by the project team.
- While the goals and deliverables for this project are well-laid-out and clear, it is not clear what value will come from attaining these goals. As a station developer, for example, each site considered has its own layout and offset requirements that are very specific, making the results of this analysis too generalized. Footprint requirements and layouts at stations are very much dependent upon the permitting offsets, the existing station equipment and layout, and the accessibility to vehicles, refueling, service, etc.
- The project team should consider starting with a base case that focuses on what needs to be done to build a hydrogen station on a greenfield site and achieve the same footprint as a gasoline station.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project is closely aligned with industry challenges; thus the accomplishments and progress are very relevant. The clear communication of assumptions provides a strong basis and trustworthiness for the results. The project team selected an appropriate level of detail with which to communicate research work and impact.
- The team has made good progress, especially in the area of identification of code issues. However, there are too many hypothetical assumptions—the project needs to take on an existing gasoline station site and take all issues into consideration (existing local requirements/preferences, adjacent structures, etc.). By the time this project is finished and the results are published, 600 kg/day can be expected to be on the low end of station capacity sizes planned for implementation; even if the project appears to push the envelope, it may not be pushing the envelope hard enough.
- The project is in its first year; to date, the results are very general and not particularly usable by a station developer or site planner.

Question 3: Collaboration and coordination

This project was rated **3.7** for its collaboration and coordination with other institutions.

- This project appears well aligned with industry leaders, public safety officials, and code development organizations. The collaboration is clearly demonstrated in the project presentation.
- The list of collaborative partners is very good and includes developers, operators, DOE, trade associations, etc.
- The project team needs to have closer collaboration with hydrogen station developers/operators in industry for practical/real input to test actual challenges by taking an existing or planned site and applying effort. This will add significant value for both industry and national laboratories.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This project is reaching its potential with regard to impact on relevance and scientifically defensible public safety requirements.
- The project has reasonable relevance/potential impact. The level of impact would change very significantly (in a positive direction) if the team took an actual gasoline or greenfield site and went through the same exercise.
- Evaluating design options to reduce the footprint of stations is very much in the purview of station developers; thus, it should not be a high priority for DOE. It is not clear what the DOE Hydrogen and Fuel Cells Program can bring to the evaluation that is not already under consideration by station developers.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- Of the proposed work, the performance-based evaluations have the most value. If a performance-based evaluation can be shown to significantly reduce offsets, and if a standardized methodology can be developed, this could be a useful tool for developers.
- The project team may want to consider eliminating rooftop storage as an option and focus all future efforts on underground storage.
- The proposed future work lacks specificity.

Project strengths:

- The project has good collaboration and input from a wide range of stakeholders. Performance-based design methodology may provide developers with an approach to reduce offsets.
- This project is very strong, both technically and in terms of relevance, and includes strong participation from industry.
- The project's strength lies in its potential impact. It is necessary for the team to assess how to reduce the footprint of equipment from hydrogen stations.

Project weaknesses:

- The project could better characterize the key concerns of public safety officials and better represent the challenges presented in the significant code changes. The team does not state how fast codes normally change, nor does the team address the concerns of local officials, despite changes in the code. It is unclear what information is needed to prevent "losing" the support of local officials, despite the code.
- Much of the project's scope is being done by developers on a project-by-project basis and will probably be too general to be applicable to any specific site.

- A weakness of this project is the modeling effort with hypothetical site scenarios. There is a need for practical applications to obtain data quickly and add value.

Recommendations for additions/deletions to project scope:

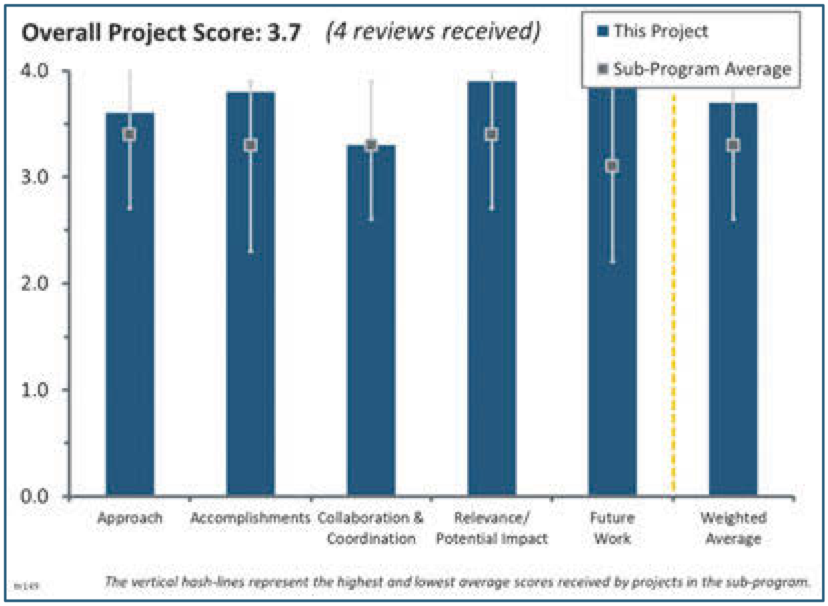
- It is recommended that a practical application to an existing or planned site be added. Rooftop storage should be removed as a future research topic; instead, the team should focus on underground storage. Instead of a national impact study, it is suggested that the team focus specifically on California and one state in the Northeast (the most challenging one)—this may help narrow efforts.
- It is recommended that the team focus future efforts on the development of a standardized approach to the performance design evaluations.

Project #TV-149: Mirai Testing

Henning Lohse-Busch; Argonne National Laboratory

Brief Summary of Project:

Argonne National Laboratory (ANL) is partnering with Transport Canada to investigate the 2017 Toyota Mirai fuel cell electric vehicle (FCEV) and provide in-depth independent and public access data for the research community. This project will utilize effective and established testing methods adjusted to the 2017 Toyota Mirai to yield real and open-source data outcomes from cutting-edge transportation technology. The team will examine energy consumption, emissions, and performance and operation at the vehicle and component levels.



Question 1: Approach to performing the work

This project was rated **3.6** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The 2017 Toyota Mirai is the first production FCEV and thus merits particular scrutiny. The project team's approach of testing and publishing actual performance data is spot-on and much needed. Testing in the ANL facilities seems very well suited for FCEVs. The team's separate supply of hydrogen prevents performance evaluation of the hydrogen supply system, but that is acceptable since the focus should rightly be on the fuel cell system.
- The project team tested and produced data from FCEV systems and subsystems. Extensive research was applied in testing and evaluating other vehicles, and the team was able to obtain the test vehicle. The project team applied its expertise in reverse engineering in this project.
- Data-gathering and public reporting are important to keep car companies honest and to allow the public to understand the vehicle's performance before buying/leasing.
- This project has a well-developed test plan that includes testing at different climate conditions. The vehicle is outfitted to maximize learning from all components.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The data presented is excellent and grants an unbiased, objective assessment of vehicle performance. The display of data, graphs with arrows, and comment bubbles was effective in illustrating key points. The definition of various efficiencies was well presented. Fuel economy was assessed at a variety of drive cycles. This is key, as results vary considerably, and comparisons between drive cycles illustrate important aspects of the power system performance. The team's evaluation at cold and hot temperatures is valuable data.
- The use of the FCEV and the infrastructure relates to DOE's H2@Scale. This project evaluates how well the car systems (i.e., the fuel cell stack and energy efficiency systems) function. These are important items to the user community at large, whether or not they understand this at the current stage of technology

adoption. The satisfaction of the user community with the FCEV is integral to the community's keeping the cars and driving them reliably. This project addresses that potential.
- It was interesting to see the energy distribution across the temperature chart, as well as the fuel efficiencies for different test cycles and the fuel cell stack efficiency and output. Also, it is interesting to understand the fuel cell behavior while the vehicle is idle to assess how much hydrogen flows out of the tanks. The test methods were appropriate.
- This project is complete and has accomplished the planned goals. Third-party assessment is essential to understanding vehicle performance. This will aid the industry in moving to fully commercial products for the market.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- Because ANL has the right expertise and adequate testing facilities, collaboration with Transport Canada and other national laboratories to acquire the vehicle and evaluate the results, respectively, is sufficient.
- Collaboration with Transport Canada is a foundation for this project. The poster (verbal) presentation did not mention other partners, but others are very likely to want to become involved.
- The collaboration with Transport Canada and the Advanced Powertrain Research Facility seems reasonable and effective.
- The project has a good collaboration with partners in Canada.

Question 4: Relevance/potential impact

This project was rated **3.9** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The adoption of FCEVs could be related to the reliability of the vehicle. At the beginning of adoption, early drivers may tolerate the need for more checkups and repairs, perhaps because they are enthusiastic. However, later on in the adoption cycle, drivers may become more critical if reliability equal to gasoline cars is not present. This ANL project gives a proactive review of the potential of reliability, which is very much needed, so that the manufacturer can benefit from a second set of eyes.
- An unbiased, open-source assessment is relevant and impactful in that it creates a base of objective facts that all can see and reference. Public dissemination of performance status allows the community to collectively identify areas that have been successful and areas that require further work.
- The project validates a state of the art of fuel cell systems in transportation and assesses technology status. These are both goals of the [former] Technology Validation sub-program.
- This project is well aligned with DOE goals and provides much-needed data and analysis on FCEVs to both DOE and the industry.

Question 5: Proposed future work

This project was rated **4.0** for its proposed future work.

- The perspective is one of planning to evaluate more FCEV models. This is extremely important. Perhaps a progression of the models as they are released would be possible. ANL discoveries and recommendations could be fed back to the manufacturers, industry analysts, and hydrogen refueling station developers so cars of the future achieve the reliability of commensurate cars with internal combustion engines. Potentially, this analysis could be used to design hydrogen refueling stations.
- This is not applicable, but it would be good to get the same results for the Honda Clarity.
- The project is complete, and no future work is planned.
- The project is complete.

Project strengths:

- The project team has a well-established facility and the capabilities to conduct testing. The plan is well-thought-out and addresses data collection under differing climates to determine how the FCEV performs.
- This analysis is necessary. How and how well the FCEV systems and subsystems work is very important to the consumer community and to hydrogen station developers.
- This project consists of professionally executed vehicle performance assessments, with the results made available to the public.
- The project's main strengths are its testing facilities, the technical expertise of the team, and its information-sharing concept.

Project weaknesses:

- The only weakness is that the user community, which can be generally intrigued with the FCEV, could have used the results of this analysis sooner. Be that as it may, the ANL approach and expertise are very good (great), and it is worth waiting for the results.
- There are no material weaknesses.
- There is no information from other hydrogen FCEVs on the market.

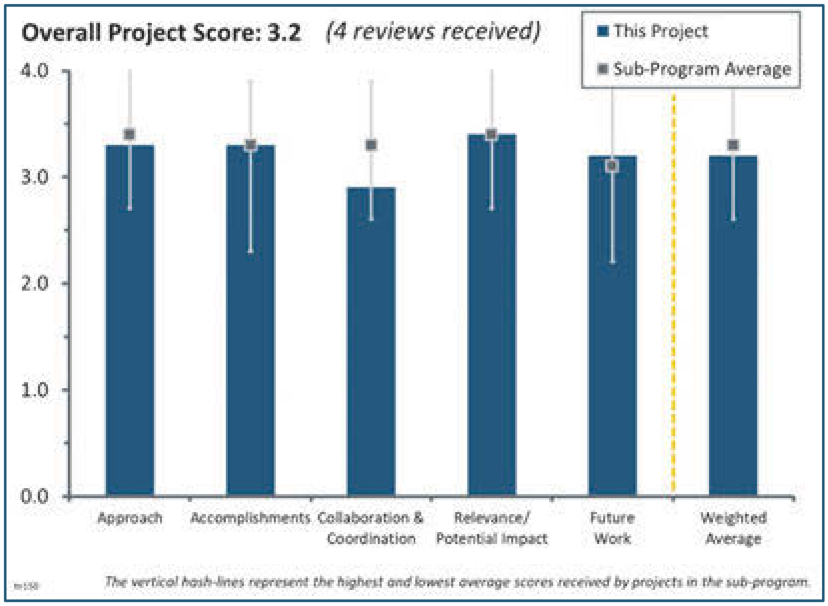
Recommendations for additions/deletions to project scope:

- This project would benefit from comparing vehicle performance simulations to the actual dyno results, particularly to evaluate what is happening at low and high environmental temperatures. More examination of cold weather power system performance would be beneficial. The source of energy losses during cold weather, while measured, is not identified. The team should address where the energy is actually going.
- It is recommended that the project team add more vehicle types to this project and future analyses. The project should investigate whether models can be evaluated prior to becoming leased or sold.
- It is recommended that the project team compare results to the Environmental Protection Agency window sticker. Other than that, the project has been completed. No additions or deletions are necessary.

Project #TV-150: Analysis of Fuel Cells for Trucks

Ram Vijayagopal; Argonne National Laboratory

Brief Summary of Project:



The primary objective of this project is to reduce the ownership cost of a fuel-cell-powered truck by finding optimal component sizes for the onboard hydrogen tank and battery pack energy storage system. The Argonne National Laboratory (ANL) Fuel Cell Team will support the U.S. Department of Energy by creating a design solution that will meet or exceed the baseline performance and cargo capacity of a conventional vehicle.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This project is a modeling optimization activity. It draws upon previously vetted models of vehicle performance and optimization algorithms, which are then used to produce believable and valuable results. The approach is excellent.
- The use of the existing Autonomie tool was appropriate, especially for the low project budget. The use of real cost of ownership (RCO) is appropriate for an overall objective function.
- The approach is appropriate, but that is not apparent in the slides provided to reviewers, as results are only for a hydrogen price of $4/gallon of gas equivalent (gge). Fortunately, the poster also had results for $12/gge, and by speaking with the principal investigator (PI), it became known that the team also ran a case for $16/gge. The PI explained that for the final results, fuel cell electric vehicles (FCEVs) and battery electric vehicles with range extenders would be compared against a diesel internal combustion engine.
- The project represents a good first step in determining methodology. Some of the assumptions (such as miles per year) might need to be looked at as variables, rather than fixed inputs.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The optimization between the sizing of the hydrogen components (fuel cell, hydrogen tanks, etc.) and the battery components (size, number, etc.) is a very important issue, particularly when balancing performance, operation cost, etc. This project was modestly funded, yet the results produced are important to the design to yield a well-balanced system to reduce cost of ownership without compromising on performance. The accomplishments are an excellent return on investment.
- The project team has illustrated the general approach by walking through a medium-duty truck case study. The graphs of the design space nicely illustrate the optimization process.
- The project represents a viable method for determining what commercial applications offer competitive opportunities for fuel cells. It would be good to show how the method can/will be expanded for use on larger classes of trucks in the future.

- The progress achieved by the team with only $25,000 is impressive. However, the slides were not up to date and thus did not do justice to the work. It is recommended that the team publish the results for the $12/gge hydrogen price, along with the original $4/gge.

Question 3: Collaboration and coordination

This project was rated **2.9** for its collaboration and coordination with other institutions.

- Given the size of the project, consulting only internally with the ANL Fuel Cell Team is appropriate. Since the project is small and builds on past analyses, it is well within the project team's capability to conduct the study with only minimal outside collaboration.
- It would be beneficial to see collaboration with auto manufacturers to get feedback and perhaps collaborate for future medium-/heavy-duty truck designs.
- An important next step would be to involve input from both truck makers and (very important) truck users/ fleet operators.
- There is some coordination between this project and outside entities (the U.S. DRIVE Partnership and Oak Ridge National Laboratory), but there are no collaborations (one cannot collaborate with oneself; i.e., this project [ANL] cannot collaborate with the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation [GREET] model [also ANL]). This project is mature enough that it needs to collaborate with an original equipment manufacturer (OEM) that is actually building hybrid fuel cell/battery trucks. Input from OEM truck builders is important to making sure the assumptions used in this effort are reasonable for the companies' needs and designs. This project is very modestly funded, but having OEMs review the assumptions used should not be a financial burden; such a review would be very valuable, establishing credibility for this effort to industry. It is the lack of this type of collaboration that resulted in a 3.0 numerical scoring, particularly since this comment was made in the previous Hydrogen and Fuel Cells Program Annual Merit Review.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- It is very important to understand this type of optimization in the vehicle design architecture and the design of the system (in this case) to minimize the cost of ownership. Other optimization parameters could be used, which might yield different results, so having such a capability is very powerful and important. This project is very relevant to the growth of this hybrid truck application.
- The fuel cell industry is starting to see trucks and commercial vehicles and equipment as more economically viable starting points for fuel cells than light-duty vehicles, so this type of analysis/toolset will enable a more rapid study of alternative approaches to enabling those applications.
- Sizing the vehicle components, while maintaining performance and minimizing cost to the consumer, helps one understand the advantages of medium-/heavy-duty vehicles, compared to the incumbent diesel technologies. This, in turn, can help one understand potential market uptake.
- The issue of fuel cell dominant versus fuel cell range extender has repeatedly come up in the analysis community. This project is timely and contributes significantly to the discussion.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The stated next steps of expanding the classes of trucks that the tool can look at and verifying the analysis process are appropriate.
- Expanding the work to additional hydrogen prices and vehicle types and comparing them against diesel trucks will be key to forecast market segmentation and potential technology adoption. Unfortunately, that was not reflected in the slides—this information was obtained from the PI.

- To date, only a single case has been analyzed. The proposed work will extend the analysis to 13 vehicle vocations. The plan to "include control parameters [within the] optimization problem" is unclear and requires further explanation.
- This project is scheduled to be completed by August 2018.

Project strengths:

- This project leverages previous validated modeling and optimization work at ANL, which increased credibility and allowed for valuable work and results to be performed in a timely and cost-effective manner. The results are excellent, as is the productivity for the very modest funding this project received. The project also used publicly available models developed as a mechanism to disseminate the results of this work; the increased capabilities of the models used in this and previous work have created value. This project is excellent.
- This project has a generally straightforward expansion of past analysis to cover the optimization of FCEVs on the basis of local ownership cost. The computational tools are well matched with the analysis requirements (i.e., the team selected the right tools for the project).
- This project addresses a key element of system design necessary to enable cost-competitive commercial applications.
- The project team has expertise in the field, particularly in the use of Autonomie.

Project weaknesses:

- The assumption of 5% depreciation loss per year may not be appropriate for fuel cell trucks. The time value of money (i.e., the discount rate) is not clearly taken into consideration in the RCO equations. It appears that the time value of money appears only in some terms. The use of the capital recovery factor is not fully explained.
- The project would have benefited greatly had there been collaboration with an OEM working in this hybrid powertrain area. The collaboration could have been a simple review by an OEM of the input parameters and assumptions made in framing the analysis.
- The project's weaknesses include low levels of funding and poor communication through the slides provided to reviewers.
- So far, the analysis has not really been validated.

Recommendations for additions/deletions to project scope:

- A sensitivity analysis would be beneficial. The optimization results should clearly identify the fuel cell power level. It is implied that fuel cell size is set by sustained highway cruising power, which implies a nearly constant fuel cell power for all configurations, but this should be explained and made clear. The cost assumptions for the fuel cell and battery need to be identified (and included in the sensitivity analysis). The meaning of the statement "the [plug-in hybrid electric vehicle] should run 50% of the daily driving distance with electric power alone" is not clear.
- It is recommended that the team look into whether there is a vehicle demonstration project or any projects that could be used as data points for the validation of the model/analysis.
- Before the slides are published, the team should ensure that results from the $12/gge and $16/gge are included.
- Recommendations for additions/deletions to the project scope are not applicable; this project is scheduled to finish up on August 2018.

2018 – Safety, Codes and Standards
Summary of Annual Merit Review of the Safety, Codes and Standards Sub-Program

Summary of Safety, Codes and Standards Sub-Program and Reviewer Comments:

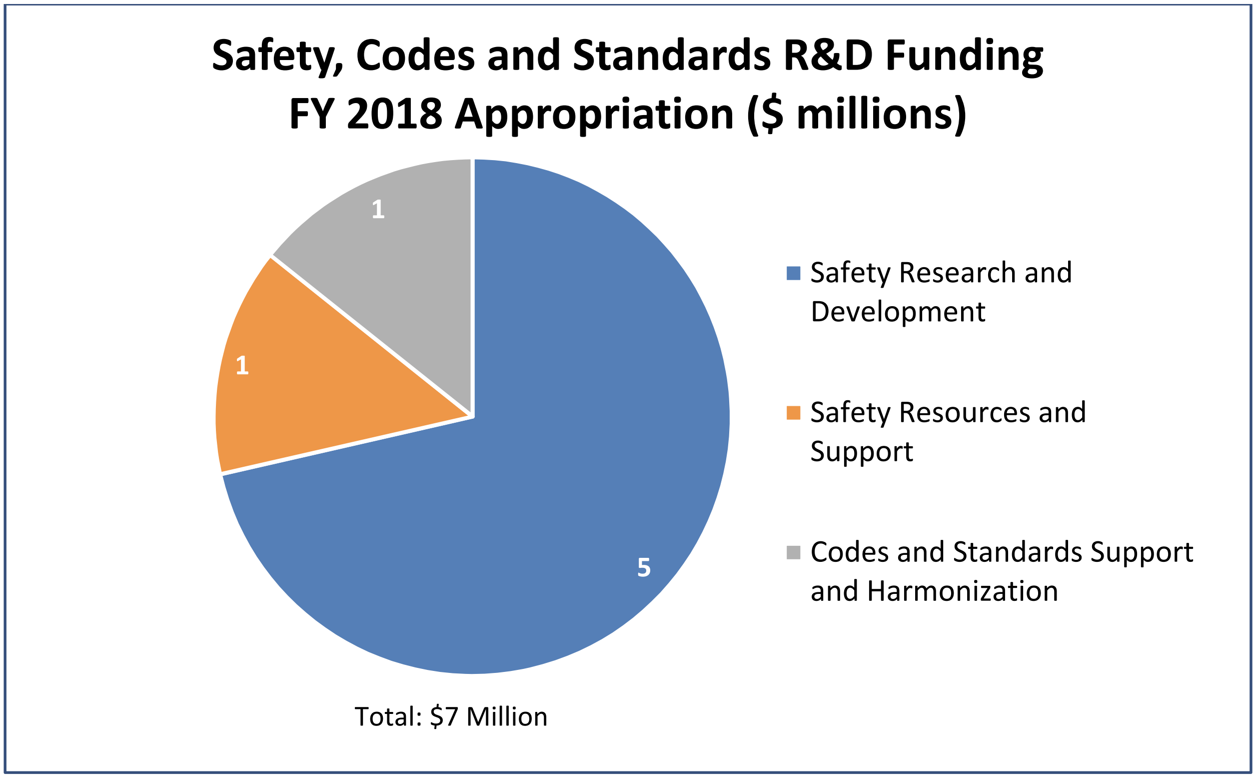
The Safety, Codes and Standards (SCS) sub-program supports research and development (R&D) that provides critical information needed to define requirements and close gaps in safety, codes and standards to enable the safe use and handling of hydrogen and fuel cell technologies. The sub-program also conducts safety activities focused on promoting safety practices among U.S. Department of Energy (DOE) projects and the development of information resources and best practices. The SCS sub-program includes research on liquefied and cryogenic hydrogen release physics, contaminant detection and sensor technology, and quantitative risk assessments and consequence analysis. The sub-program also focuses on domestic and global codes and standards harmonization to enable large- and small-scale hydrogen applications.

Hydrogen and Fuel Cells Program reviewers were highly supportive of the SCS projects and noted that the work of the SCS sub-program enables accomplishment of the broader goals of DOE and the Fuel Cell Technologies Office. The collaborations in many of the projects were seen as much improved, as was the progress made since the previous year in projects related to hydrogen behavior, national codes engagement, materials compatibility, and fuel quality. Reviewers continued to praise the science-based approach and the provision of feedback to code development organizations and standards development organizations. However, reviewers recommended that the H2@Scale concept be broken out into specific activities with better-defined scope and resources to incorporate it into this sub-program. Reviewers indicated support for outreach projects, including H2Tools.org, and encouraged the direction of additional resources for this critical work in educating regulators and responders. Key recommendations for SCS R&D included development of fueling protocols for medium- and heavy-duty fuel cell electric vehicles and continued emphasis on hydrogen contaminant detection, incuding preventative maintenance of the devices and validation of the prototype devices.

Safety, Codes and Standards Funding:

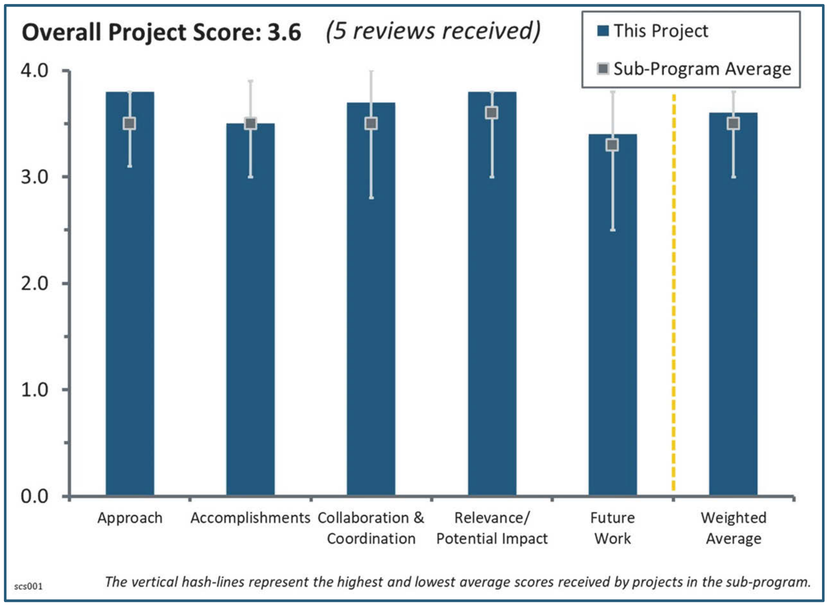
The FY 2018 appropriation for the SCS sub-program totaled $7 million. The funding was focused on safety R&D and is depicted in the following figure. The funding is expected to provide continued support of SCS R&D and efforts on domestic and international collaboration and harmonization of codes and standards. Future work in the sub-program is expected to focus on facilitating reduced regulatory barriers, such as by providing scientific anlaysis for revised bulk liquid hydrogen separation distances.

Nine projects were reviewed, receiving scores ranging from 3.4 to 3.75, with an average score of 3.53. Each of the following project reports contains a project summary, the project’s overall score and average scores for each question, and the project-level reviewer comments.


Safety, Codes and Standards R&D Funding
FY 2018 Appropriation ($ millions)
1
1
5
Safety Research and Development
Safety Resources and Support
Codes and Standards Support and Harmonization
Total: $7 Million

Project #SCS-001: National Codes and Standards Deployment and Outreach

Carl Rivkin; National Renewable Energy Laboratory



Brief Summary of Project:

The objective of this project is to further the deployment of hydrogen fuel cell technologies with particular focus on the infrastructure required to support fuel cell electric vehicles. This outreach and training project supports technology deployment by providing codes and standards information to project developers and code officials, making project permitting smoother and faster.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach to this work is excellent and ever-evolving. This principal investigator (PI) is getting better at working with others (Inter-Laboratory Research Integration Group [IRIG]) and dissemination of the work into places where authorities having jurisdiction (AHJs) and others are most likely to find it. The Continuous Codes & Standards Improvement (CCSI) process aggressively seeks to integrate scientific research into the code process, which is excellent. In addition, the active outreach to first responders and AHJs is very good.
- The project addresses identified barriers very well. The project is effective and well integrated with National Fire Protection Agency (NFPA) 2 to a great extent, and to other relevant codes and standards activities to some extent. The approach allows for a holistic approach to identifying safety concerns, conducting research, and feeding that work into developing codes and standards, with an appropriate emphasis on NFPA 2.
- The approach is excellent: integrating research into the codes and making the information available to all kinds of users in a form that matches their needs in a location that they expect to find it.
- The project is clearly defined and extracts actionable tasks that make significant progress against overarching objectives.
- This project has done a much better job of aligning with appropriate and necessary activities.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The development of a "standard" permitting guide should dramatically help reduce time and cost for permitting hydrogen fueling station deployment. When asked about how to reach the 44,000 AHJs, the answer was to put this as an appendix on NFPA 2, which has already been adopted (in one way or another) in every state in the nation. It was an excellent answer. The PI identified unexpected hydrogen behavior associated with venting from the National Renewable Energy Laboratory's (NREL's) fueling station and hydrogen vented from test bays. While hydrogen properties are widely understood, in many scenarios, hydrogen behavior is not understood. NREL will likely work with others in the hydrogen community to dispel the well-published myth that just because hydrogen is 14.4 times lighter than air, and its molecular

diffusivity is ~3.8 times that of methane, it does not necessarily go up and diffuse rapidly. This is a myth that can be dangerous if applied when indeed hydrogen does not behave in that manner, as in the two examples presented during this presentation.
- Significant and impressive progress has been made with regard to hydrogen safety outreach and increasing accessibility for useful hydrogen safety information. Additionally, significant progress has been made on closing the loop on the codes and standards revision process that addresses barriers with regard to hydrogen safety. One suggestion is also to include barriers for hydrogen fuel cell deployment that are not safety-related, such as public and community benefits, and information that can be made available to localities (in the context of permitting and within the scope of the project) that increase support for hydrogen fuel cell technologies from an environmental or economic benefit perspective. Safety-related barriers are only one of many categories of barriers to increased deployment.
- Accomplishments made in the past year are overall much better than in previous years. There are still concerns with the precedent of equating success with leading task groups and standards efforts, which should be led by commercial participants, and adding research to fire codes and standards, as this could lead to efforts that are counter-productive to industry needs or that over-complicate the regulations. The more appropriate efforts of publications, particularly in non-scientific periodicals, code summaries, code training, videos, etc., are excellent accomplishments and examples of a very useful precedent that will be needed for years to come. While some of the leadership of task groups and research added to fire codes has been very helpful, this should not be the ongoing measure of success for this project. The project ambitions should identify very specific areas where leadership or research is needed and direct more efforts to the outreach efforts.
- The project is making excellent progress toward the DOE goals. While many would like to see the work move even faster, the project is moving steadily forward at a pace supported by the availability of data and resources, as well as code development schedules.
- Some referenced resources are quickly becoming outdated (e.g., the Certification Guide by the Hydrogen Safety Panel, the AHJ video). The Standard Permit Task Group and its deliverable are very positive. The paper for the American Society of Safety Engineers Journal needs some discussion, or at least the findings do. This is potentially critical to outreach and messaging of hydrogen to AHJs and first responders.

Question 3: Collaboration and coordination

This project was rated **3.7** for its collaboration and coordination with other institutions.

- The project utilizes excellent collaboration and coordination with other institutions and relevant stakeholders. Use of IRIG ensures related research efforts throughout DOE laboratories are well coordinated. Leadership of NFPA 2 development, as well as task forces to address specific issues, ensures industry and other stakeholders are engaged to help solve issues as they arise and learnings are shared.
- A clear strength of this project is that the team has been very effective in collaboration and coordination with other institutions.
- This project does an excellent job of coordinating many stakeholders.
- This project has been criticized in the past for not being better connected (in collaboration) with other DOE resources (i.e., national laboratories). With the creation of the IRIG, much of this criticism has been removed. The PI has also developed an impressive, well-balanced set of collaborators, mostly through his work with NFPA. It is anticipated that this new collaborative posture will continue and grow as the community understands what needs to be done with regulations, codes, and standards (RCS) as we transition to H2@Scale. It would still be good to see this project be more assertive in finding collaborators and coordination with others. In answer to a reviewer comment, “NREL would welcome any opportunities for additional collaboration and identification of special programs that should be connected to this work,” it would be good to see NREL be assertive in identifying these opportunities rather than waiting for them to avail themselves to NREL.
- Collaboration could be more transparent, and there could be better communication about the opportunities to collaborate. For example, the NFPA task groups are not always transparent/known about initially. It is unclear whether the code gap analysis is done and available.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The CCSI project enables the safe deployment of hydrogen fuel cell technologies by informing the development of required codes with science-based data, and appropriately engages industry experts and other stakeholders to target critical issues and disseminate learnings. The Codes and Standards Outreach and Training project supports technology deployment by engaging and providing needed information directly to project developers and code officials, making project permitting smoother and faster.
- This project is highly relevant and has had a significant impact with regards to hydrogen safety, awareness, outreach, and education. Focus on other, non-safety-related barriers may make an even larger impact toward deployment cost objectives of the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan (MYRDDP). H2@Scale focus is critical to increasing public awareness and acceptance of hydrogen technologies.
- Like the Sandia National Laboratories project, "Enabling Hydrogen Infrastructure through Science-Based Codes and Standards," this work is also imperative to the advancement of the hydrogen economy and to the safety, codes and standards community.
- This project is key to deploying and improving critical RCS to deploy hydrogen technologies in a safe and expedient manner.
- This project is having a real and lasting impact in hydrogen energy. The project should consider a panel of stakeholders to provide guidance on future efforts.

Question 5: Proposed future work

This project was rated **3.4** for its proposed future work.

- The PI should continue the open collaboration with all others in the community to ensure the best results. Communication is key.
- With the foundation developed for cooperation/collaborations, mechanisms to incorporate science into the code development, taking this to H_2@Scale is very good and should greatly help accelerate and remove critical barriers to the deployment of hydrogen technologies at scale.
- Future work proposed on H2@Scale is a plus. Larger, not-yet-seen hydrogen projects are on the horizon, and this project promises to stay ahead of that curve.
- This project struggles with soliciting and listening to input from stakeholders. A standing panel of stakeholders that review and advise this project's direction would be much more efficient. While this project has great success and impact, a great deal of effort is expended trying to corral this project, as it tends to initiate projects that must be significantly changed to result in that success.
- In addition to continuing to make progress on NFPA 2 issues and educating permitting officials, the project will expand the focus to encompass the larger scope of H2@Scale. While this is necessary, the scale of the effort will need to ramp up to avoid a significant slowing of results on the current efforts.

Project strengths:

- This project does an excellent job at holistically addressing barriers in codes and standards with a focus on NFPA 2: The Hydrogen Technologies Code. The effort also serves a critical role of providing necessary information to code officials and other stakeholders to help accelerate the safe deployment of hydrogen technologies. The project also ties codes and standards development needs with science-based research and dissemination of learnings.
- The overall project strengths include collaboration/cooperation with a wide variety of stakeholders and beneficiaries, project management and project focus, and future work with a focus on H2@Scale (much-needed and valued work to ensure success in the marketplace and toward MYRDDP targets).

- This project is at the core of identifying and generating RCS to remove barriers to the safe deployment of hydrogen technologies. This project has significantly improved its collaboration and coordination with other RCS groups inside and outside the Hydrogen and Fuel Cells Program.
- This project has timely and pointed goals and deliverables to enable the hydrogen community.

Project weaknesses:

- While it is not necessarily a weakness, transparency, communication, and collaboration are imperative to success for all.
- The project objective is to further enable the safe deployment of hydrogen fuel cell technologies. While hydrogen safety and safety-related outreach and education are clear priorities to meeting this objective, non-safety-related work can have a significant impact on the project objective. For example, experience permitting hydrogen fueling stations has shown that fire safety is a contributing barrier to deployment. However, a general lack of understanding of the benefits of hydrogen technologies to communities, the workforce, and the energy economy are also contributing factors to the technologies' lack of priority in the community project roster. This will be increasingly important with an H2@Scale focus.
- The planned increase in scope to cover potential gaps in H2@Scale opportunities is a large order. It would be useful to understand the impact of such efforts on the project duration and funding requirements for the future, as well as the ability of the project to meet the timeliness needs for NFPA 2 activities. It would also be good to see plans for disseminating learnings that currently have no specific code or standard focus. For example, slide 13 of the presentation found that hydrogen venting from experiments involving multiple fuelings has migrated into nearby work areas where it was not expected to accumulate, and hydrogen vented from indoor test bays into stacks serving multiple sources has been driven back into work spaces. The presentation noted that such findings will be documented. The project should consider publication in safety-related articles so that the safety community can learn about these situations quickly and begin to better understand the mechanisms noted.
- The project can still improve its reach internationally.

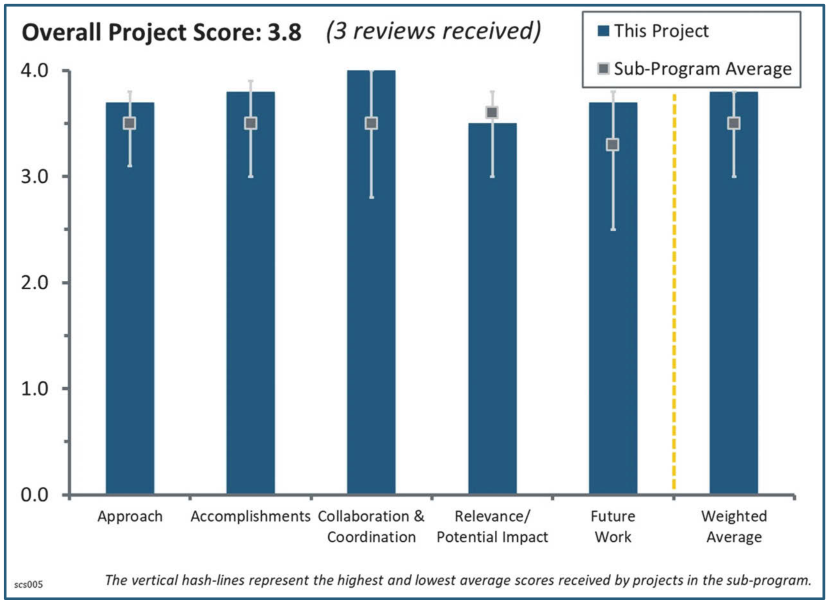
Recommendations for additions/deletions to project scope:

- Expanding the scope to H2@Scale is already a huge addition. It would be good to see that concept broken out into specific activities with a better idea of the scope and necessary funding. An expansion of the project team will likely be necessary.
- This project needs to start embracing an international component to its overall scope; the project would benefit greatly.
- The addition of community, workforce, and energy economy benefits of the technologies will improve progress toward the project objective.

Project #SCS-005: Research and Development for Safety, Codes and Standards: Materials and Component Compatibility

Chris San Marchi; Sandia National Laboratories

Brief Summary of Project:



The main goal of this project is to enable technology deployment by providing science-based resources for standards and hydrogen component development and to participate directly in formulating standards. The project will (1) develop and maintain a materials property database and identify materials property data gaps, (2) develop more efficient and reliable materials test methods in standards, (3) develop design and safety qualification standards for components and materials testing standards, and (4) execute materials testing to address targeted data gaps in standards and critical technology development.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project approach has an excellent focus on the key parameters associated with hydrogen compatibility for metallic materials. The project researchers have the appropriate balance of experimental evaluation and practical application guidance.
- A set of austenitic stainless steels with varying strengths and nickel content is investigated under uniaxial cyclic loading to calculate the fatigue life dependence on hydrogen pressure and temperature. The conservative assessment of life through notched specimens is also addressed. Next, the resistance of the steels to fatigue crack growth is assessed by using the acceleration technique through the load parameter C. Because it is well known that hydrogen degradation is more pronounced at low frequencies, the acceleration approach needs to be carefully ascertained. Given the capabilities of the Sandia National Laboratories (SNL), the need for an accelerated testing approach is unclear.
- This project activity directly addresses present industry needs.

Question 2: Accomplishments and progress

This project was rated **3.8** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project successfully completed the testing of notched tension–tension specimens (conservative approach) and demonstrated small variability of life among the steels tested. In the case of resistance to fatigue crack growth, the project successfully demonstrated that steels with tensile strength less than 950 MPa also behave similarly and came with a fitting curve for fatigue crack growth rate (da/dN) vs. the change in stress intensity factor (dK). In particular, for steels with strength greater than 950 MPa, the project established that the fatigue resistance becomes uncomfortably low.

- The project had a significant accomplishment this year by establishing a generic fatigue crack growth curve and providing this to the ASME committee. The project continues to make excellent progress in evaluating materials and distributing results to various stakeholders.
- As conveyed by the principal investigator (PI), fiscal year 2018 milestones are being met.

Question 3: Collaboration and coordination

This project was rated **4.0** for its collaboration and coordination with other institutions.

- The project is an example for other projects in the Safety, Codes and Standards portfolio to follow. The project verifies results through round robin testing, collaborates with experts both domestic and international, and disseminates the results to relevant codes and standards. In particular, the project provided results to the Global Technical Regulation Phase 2 effort, which is a global collaboration with industry.
- Collaboration with Kyushu is most excellent. Kyushu has tremendous testing capabilities, among the world’s best.
- Collaboration was well considered and included excellent partners.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is highly relevant for the fundamental determination of metal compatibility in hydrogen applications. The potential impact of the project is unknown for on-board storage systems, as there is limited stainless steel used and aluminum is a material that is often used for valves and other components. In addition, the other materials being evaluated may not result in a cost savings owing to other factors. Regardless, the effort provides the necessary data for the codes and standards.
- The project is extremely relevant and meets all requirements of the Hydrogen and Fuel Cells Program. The project provides a wealth of required data for the design of high-pressure hydrogen fuel systems (performance-based) and stationary pressure vessels (design-based).
- Research was conceived to target industries with information they considered valuable. The findings are coordinated with standards organizations and published through an online database.

Question 5: Proposed future work

This project was rated **3.7** for its proposed future work.

- Low-temperature response, ratio of minimum peak stress to maximum peak stress (R-ratio) effects on crack growth, understanding the mechanics of notched specimens, and the probing of microstructural length scales are all outstanding issues that need investigation.
- The future work appears to build on the past effort effectively, although the PI should consider a specific plan to assess aluminum alloys. Reducing the test effort with lower R-ratios and reducing the complexity of lower-temperature testing—these goals are worthwhile.
- The project’s proposed future work is in line with goals.

Project strengths:

- The strengths of this project include the following: the project targets information needed by industry stakeholders, research elaborates important relationships in data to promote future prediction, findings are coordinated with standards organizations, partners and collaborations are strong, and data are made available to the public.

- The project strength is the fundamental approach of the experimental designs and the effort to challenge the historical test methodologies. The project also does an excellent job in communicating and participating in codes and standards development.
- The strengths of this project include the experimental capabilities of SNL; collaborations with Kyushu University; and the capabilities, knowledge, and general expertise of Chris San Marchi.

Project weaknesses:

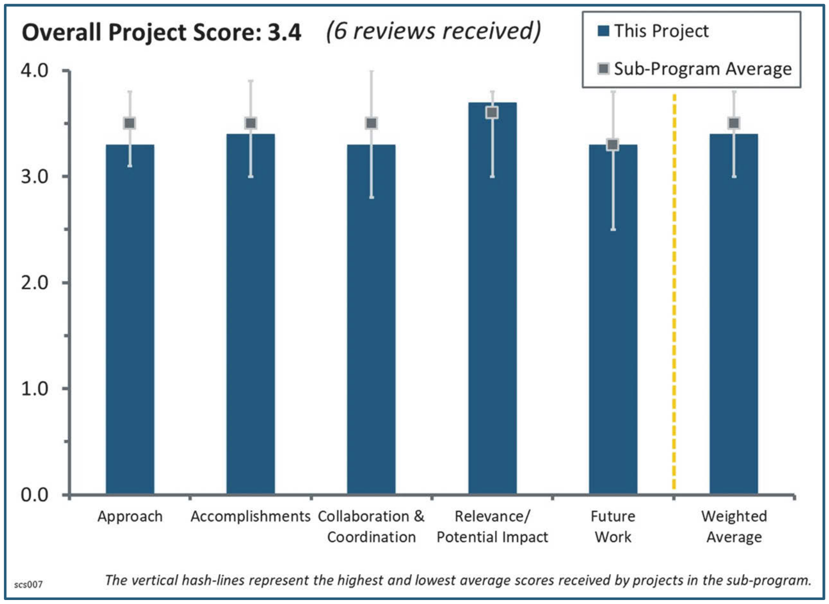
- The project lacks mechanics modeling to account for and assess the influence of the microstructure of austenitics on fatigue life and crack growth. This wealth of experimentally obtained results is not assessed and explained from a mechanistic perspective.
- The weakness of the project is the uncertain impact of the results. The verification of new materials may be costly using these methods and may fail to result in significant improvements in cost or function over the current material (i.e., low-carbon stainless steel 316L). It would be helpful to expand the project scope to include aluminum.
- The reviewer is not a metals expert and is not aware of gaps, so weaknesses in the work are not apparent. More could be said about the data management plan.

Recommendations for additions/deletions to project scope:

- The project scope is good, although aluminum should be considered in the near term. In addition, it would be helpful to work with a component supplier to develop a component using an alternative stainless steel material to quantify the benefit. Any effort to simplify the test method and ensure laboratories other than a national or specialized laboratory can conduct the test would be helpful.
- Modeling and simulation should be incorporated into the project scope. The accelerated testing approach needs to be carefully validated in a systematic way in terms of the response in low frequencies and high-load ratio. There is no obvious rationale for such an approach.

Project #SCS-007: Fuel Quality Assurance Research and Development and Impurity Testing in Support of Codes and Standards

Tommy Rockward; Los Alamos National Laboratory



Brief Summary of Project:

The objectives of this project are to (1) focus on polymer electrolyte membrane (PEM) fuel cell testing and collaborations and work with the American Society for Testing and Materials to develop standards and (2) develop an electrochemical analyzer to measure impurities in the fuel stream. The analyzer will be inexpensive, will be sensitive to the same impurities that would poison a fuel cell stack, and will support quick responses to contaminants.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The notion of using PEM hardware to detect contaminants that will poison PEM fuel cells is excellent. Support for this approach to develop a fuel quality sensor has existed from the beginning. The methodical, systematic approach to the development of this sensor is spot-on.
- The ability to monitor, in real time, the quality of hydrogen fuel at the station is important. Most impurities will be introduced to the fuel because of poor hose cleaning and/or equipment failures. This makes measurements “at the nozzle” important.
- The project approach combines development of the fuel quality analyzer with field testing activities to support meeting SAE International J2719 fuel quality limits. The approach is appropriate for this type of work. The use of a fuel cell as an in-line sensor is worthy of investigation. The main shortcoming in the approach is the lack of clear targets to evaluate success of the device in terms of cost, effectiveness, response time, sensitivity, reliability, etc. There is also a need for benchmarking device performance.
- The approach seems appropriate. Analysis of the fuel to ensure that it meets the purity standard is important. The only concern is that a small amount of fuel (sidestream) flows through the analyzer, which may not give a true picture or a timely assessment of the fuel.
- The approach reflects a progression to a more refined design, patent, and field trial. Making sure there is a clear plan to move to practical deployment at scale would be beneficial.
- The approach to install an in-line fuel quality analyzer to improve reliability of the infrastructure is important. However, it does not seem certain that the analyzer is sufficiently in-line with the fueling for field trials.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The patent, a culmination of a multiyear development effort, indicates a notable accomplishment. The demonstration of necessary response time specifications and field experiment implementation in Burbank are noted as accomplishments.

- Timely progress toward the goal has been achieved. The deployment of an in-field analyzer shows good progress toward the goal. The next step of determining how the device works in the field should provide a better assessment of whether the goals will be met.
- A response to 200 ppb CO was demonstrated. It was noted that a provisional patent was applied for in November 2016. Provisional patents are good for only one year, so a question remains as to whether the patent was filed and awarded yet. Progress in field trials is excellent. However, the principal investigator should consider rethinking the application of this technology. The response time of ~1.5 to 6 minutes, depending on the threshold level, is too long to detect an upset during any one fill, especially considering the flow times associated with actually delivering the sample to the detector. In addition, this detector, in its current configuration, will not be able to handle a -40°C and 70 MPa fill environment. This does not mean that the sensor does not have enormous value. It just means that the target application/location and response timescales dictate a re-thinking of the sensor's exact optimal value application/installation. This is particularly true given that different species are to be considered, such as H_2S, which could be introduced into the fuel as late in the system as the nozzle if a recent cleaning or repair occurs. This technology and its application to fueling stations is good; it is just that its optimal application may not be attempting to detect a fueling contamination during a single fueling event and catch the contamination on that fill. The timescales are just not good enough to catch such an event in a three-minute fill.
- The membrane hydration challenge was solved with the wicking scheme system, and the electrode performance with larger baseline currents is making great progress. Optimizing downtime for cleanup voltage will help with throughput.
- The biggest accomplishments are the installation of the prototype analyzer in the field at the H2 Frontier site and the establishment of remote monitoring capabilities at Los Alamos National Laboratory (LANL). This is a big step forward. The patent filing is also an important step. The rest of the progress is less clear. Several of the slides differ minimally from what was presented last year. Slide 8 discusses a milestone to identify and address the cause of baseline current drift, but it was not clear where the result of this was presented. Some drift is attributed to humidification, but there are no plots showing the effect of humidification on drift. The drift is still visible in plots on slides 8–10. It is questionable whether the clean-up strategy is appropriate, given that contaminated hydrogen supply would not reset between vehicle fuelings.
- Several questions came to mind. It is unclear if the plan for the 15-minute recovery time, as indicated on Slide 8, is part of the station powering up in the morning or something else. Slide 9 was (seemingly) showing the loss rate contamination or tortuosity (water balance). Given that the response time is around 90 seconds for 20 ppm CO and 230 seconds for 500 ppb, it is unclear how far back into the system one has to be to prevent vehicle contamination.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The collaboration partnership with H2 Frontier should yield excellent data and provide the analyzer with a path for future improvements and experiments. The involvement with the International Hydrogen Delivery Risk Assessment and Impurity Tolerance Evaluation (HYDRAITE) meeting was successful.
- There is good coordination between the developer of the test apparatus and the end user, which allows field testing of the test apparatus.
- The collaborators and cooperation are appropriate for this project. The only reason the project did not received a 4.0 score was its lack of international cooperation, specifically the International Organization for Standardization (ISO) Technical Committee 197 with 14687 fuel quality. Admittedly, ISO 14687 and SAE J2719 are well harmonized, but ISO 14687 is undergoing revision, and to contribute to and stay on top of that work would benefit this project greatly.
- Collaboration between LANL and the station partners is excellent. The main shortcoming is the lack of communication with similar efforts internationally.
- Collaboration with Lawrence Livermore National Laboratory and H2 Frontier on field studies has been coordinated. The initial connection with the HYDRAITE community in Germany is noted, but the tangible outcomes of the outreach are not clear. Additional collaboration might help facilitate and address practical deployment.

- It was surprising to not see MSA Safety, Inc., or Detronics involved, both of which are major combustible gas sensor suppliers.

Question 4: Relevance/potential impact

This project was rated **3.7** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Ensuring fuel quality is important to ensure that vehicles do not have problems. Poor fuel quality will cause consumers to question vehicle viability. The analysis of the fuel quality will help to promote vehicle deployment.
- This project is extremely relevant and urgent for ensuring the reliability of hydrogen infrastructure and vehicles during early commercialization.
- This project has a very important relevance to the industry, as contaminated fuel has the potential to bring on problems for a vehicle's fuel system.
- The effective mitigation of degradation from contaminants is relevant and aligns with Hydrogen and Fuel Cells Program objectives. The project is showing progress toward a field-tested solution to address CO.
- Fuel quality control and monitoring at the station is critical to ensure the safe deployment of hydrogen technologies such as those found in fuel cell electric vehicles. Smooth deployment and success of the technology, particularly in these early deployment times, is critical.
- The potential impact is to protect the PEM fleet. The cost estimates, though, are unclear.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The future work is neatly divided into both field experiments and continued research and development (R&D) in the laboratory. Having remote access to the analyzer should help the effort understand analyzer needs, such as maintenance. The R&D laboratory work will provide the team with an opportunity to study the effects of other contaminants, such as H_2S, in the fuel supply.
- Plans to address operating improvements and other contaminants are relevant and practical extensions.
- This seems reasonable.
- Field deployment of the analyzer is the next step in the process. Determining where to draw the stream to be analyzed is something that must be determined, and it is critical to ensure that the fuel sample to be analyzed be representative of the fuel as a whole. The small amount of fuel that is analyzed may not be representative of the bulk source.
- Future work on the field experiments is consistent with what is expected from a recently installed prototype device, although the presentation lacks specifics about test design. The future R&D work is vague. Many ideas are presented, but there is no timeline or priority given. It is unclear how feasible any of these ideas are.
- It is strongly suggested that the team rethink how to best use this technology to ensure adherence to the fuel quality standards. The notion that this detector can actually detect a fuel quality upset during any one fill is not realistic because of characteristic times to deliver the sample to the detector, the characteristic time for the detector to respond, the environment in which the detector can and needs to respond, and the time over which a fill actually takes place (three to five minutes). The suggestion is to recast the application into a more realistic scenario or application.

Project strengths:

- In-field, real-time analysis of fuel is something that could provide critical information to ensure that vehicle fuel cells are not poisoned by poor-quality fuel. Field deployment of the device and future data collection should provide a level of comfort that high-quality fuel is being produced.

- The field testing of the fuel quality analyzer adds significant value to establishing the effectiveness of the prototype in a real-world environment. The project includes good partnerships between national laboratories and industry.
- The project team has the technical knowledge and planning capability to develop an impurity detector. The partnership with the H2 Frontier station in Burbank is allowing for real-time data collection.
- Project strengths include a relevant focus on mitigating damage, sustained refinement of the design, and a practical version being actively field-tested.
- This is a very intriguing technology, and it is showing very impressive results.
- The expertise of the laboratory is a project strength.

Project weaknesses:

- The principal investigator and DOE need to recast the specific application with respect to fueling stations to redirect some of the goals and targets to more closely align with realistic timescales and sensitivities. A previous reviewer remarked on not having enough time and money to work at a faster pace, noting that fuel quality assurance technologies are needed in place now, because hydrogen fueling stations are being deployed in California now and in the Northeast soon.
- Having the analyzer function with a response time of under five minutes is critical. It is a bit misleading that the analyzer is installed at the Burbank station, but it is not in-line, and it does not analyze fuel at 700 bar. The placement of the analyzer is a problem for detecting CO and H_2S; the location could be moved, but then there may be a temperature or pressure problem.
- The project might benefit from more active and expanded collaborations around specific, scaled, and practical deployment plans.
- There is a lack of clear metrics to define the analyzer's success. There is an unclear timeline for moving beyond the prototype, as well.
- Ensuring that the obtained fuel sample is representative of the bulk fuel is a concern, as is any potential ongoing maintenance activities that are required to ensure that the device remains viable.
- A question remains about who will develop this prototype into a commercial piece of equipment.

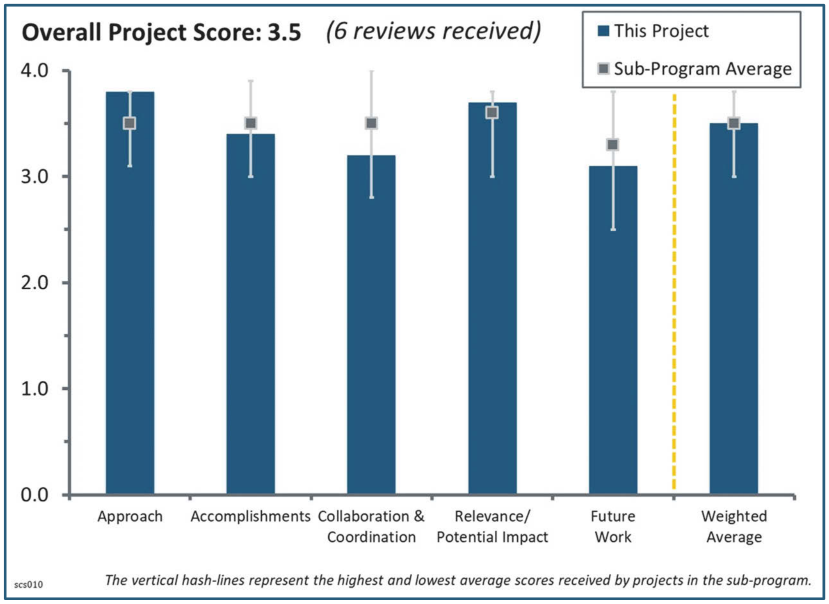
Recommendations for additions/deletions to project scope:

- The project should make a determination as to whether there is any required preventative maintenance on the device that must be investigated. The enclosure must be assessed to ensure it is intrinsically safe. If there are ignition sources within the enclosure and a hydrogen leak were to occur, the results could be detrimental.
- A plan should be added to validate the prototype measurements. The non-dispersive infrared CO analyzer at the H2 Frontier site provides an opportunity here.
- The project should rethink the precise application's location in the station and how it can be used to maximum benefit.
- Additional clarity on the operating costs, durability, and similar aspects would be important to moving forward.
- The project should continue to study the Burbank location installation to determine whether results are reliable and repeatable.
- The project should find a partner who can commercialize the prototype.

Project #SCS-010: Research and Development for Safety, Codes and Standards: Hydrogen Behavior

Ethan Hecht; Sandia National Laboratories

Brief Summary of Project:



The project's purpose is to perform research and development to provide the science and engineering basis for the release, ignition, and combustion behavior of hydrogen across its range of use (including high-pressure and cryogenic). The research includes model and tool development to facilitate the assessment of the safety (i.e., risk) of hydrogen systems and enable use of that information for revising regulations, codes, and standards and for permitting stations. Sandia National Laboratories (SNL) is working to address the lack of safety data and technical information relevant to the development of safety codes and standards by (1) providing a science and engineering basis for understanding the release, ignition, and combustion behavior of hydrogen across its range of use (i.e., high-pressure, cryogenic), (2) generating data to address targeted gaps in the understanding of hydrogen behavior physics (and modeling), and (3) developing and validating scientific models to facilitate quantitative risk assessment (QRA) of hydrogen systems and enable revision of regulations, codes, and standards to accelerate permitting of hydrogen refueling. The project began in 2003.

Question 1: Approach to performing the work

This project was rated **3.8** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The issue is providing science-based data for separation distances to support development of liquid hydrogen (LH2) storage and dispensing centers and related standards. This effort gets good marks for a careful and systematic approach to understanding hydrogen release behaviors.
    - That said, the project should approach one step at a time by looking first at cold gas dispersion and pursuing liquid spill behaviors later. However, it is important that the liquid spill behaviors be addressed in the future because of known possible behaviors that are very hazardous and because of the large quantities of LH2 that will be needed to service future hydrogen infrastructure. The concern is the limited budget provided for this effort.
    - Careful process of elimination on measurement techniques was considered. From experience, past measurement techniques are difficult to deploy and have only crudely addressed measurement of hydrogen dispersion. The proposed Raman approach holds the best promise for providing sufficient detail, but adapting that approach from a laboratory setting to a medium-scale environment will still be difficult. The SNL Thermal Test Facility is a good choice for a medium-scale environment with controls.
    - Incorporating findings into models made available to the public addresses the data management plan.
- The project's goals and objectives are simple and clearly stated. Therefore, the approach is very well laid out. Gaps in the data for the release, ignition, and combustion behavior of both high-pressure and cryogenic

hydrogen will be addressed by developing scientific models to predict hazards and methods of QRA, and then applying those models to real-world situations.
- The project team has an excellent approach to this work of developing the methods and models and including the implementation of experimental work to validate the modeling work.
- The scientific problem tackled is critical to the whole success of hydrogen technology. Knowledge of LH2 behavior is still in its infancy, including the methodology to study it.
- The approach is carefully thought out, designed, and implemented.
- The approach is questionable. It is unclear why the project team did not use both sensors and optical diagnostics if neither technique is entirely suitable for the application. It is unclear why a thermal map was not generated as part of the "sensors."

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project has made a significant advancement in the scientific understanding of the behavior of hydrogen plumes and flames at very low temperature. The project shows great promise with regard to informing the national fire codes on revised separation distances, which has the potential to reduce station footprint and siting and thereby decrease the cost of fuel by allowing more distribution of LH2 to fueling stations, in line with DOE goals. Large-scale testing may be a challenge in terms of schedule and scope.
- The project has made excellent progress in 2018 to develop and validate a ColdPLUME model for cryogenic hydrogen leaks in a laboratory-type situation. This progress includes evaluating various techniques to measure the dispersion.
- This project has shown excellent progress, mainly around the Raman imaging results and on the validation of the ColdPLUME model for laboratory-scale hydrogen release.
- This effort faces many difficulties, but the project team has overcome them and continues to make progress. However, the progress is confined to cryogenic gas dispersion. The concern is that funding may dry up before other significant experiments on liquid behaviors can be addressed. These future activities are addressed only as remaining challenges.
- The project has set very ambitious targets and shows visible progress. The targets may be too ambitious. It does not seem credible that it will be possible to characterize scaled-up release, including pooling and realistic environmental conditions, with the given funding and the still-existing challenges of the chosen diagnostics tool.
- The "accomplishments" contradict the "approach." The accomplishments to date show progress. It is not clear whether the experience with instrumentation can be applied to low-cost leakage sensors.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- The sound design of realistic LH2 release experiments is very challenging and will benefit from an international effort. The fact that an interface is now in place with the European Project, Prenormative Research for Safe Use of Liquid Hydrogen, and with Chinese experts is extremely good, and these connections should be developed further.
- The project has very good collaboration with external stakeholders. The constant interaction with the National Fire Protection Agency 2 Technical Committee is essential for the success of this project.
- Collaboration and coordination with industry, academia, and code-setting organizations are good. Several cooperative research and development agreements (CRADAs) are in place.
- Collaboration and coordination with other institutions has been good, especially among experts. It is recommended that the project increase collaboration with members of industry associations, such as the American Petroleum Institute and the Compressed Gas Association.
- The presentation did not make clear how, or if, the partners had contributed to the present progress. Air Liquide was mentioned as participating in an H2@Scale CRADA that will accelerate progress, but how this would occur was not elaborated. In the past, Germany's Federal Institute for Materials Research and

Testing has performed spill experiments, and various Japanese research efforts have sought to model spill behaviors, but it is not known whether these organizations are still involved in this research. In the more distant past (1980), NASA performed moderate-scale (1500-gallon) LH2 spills, but at present NASA is not investing resources in further study (i.e., no shuttle or space launch systems are in development).
- The partners (slide 2) and collaborators (slide 15) do not agree. It is not clear how Shandong and the Fuel Cells and Hydrogen Joint Undertaking add value. Air Products and Chemicals, Inc., and NASA White Sands might be of more technical value.

Question 4: Relevance/potential impact

This project was rated **3.7** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This work is of extreme importance to the hydrogen and fuel cell community, mainly in the transportation sector. As more hydrogen stations are coming online and the ramp-up in the deployment of hydrogen fuel cell vehicles keeps moving forward, the transition to liquid hydrogen stations will soon be approaching. Having a clear understanding of the safety aspects of liquid hydrogen is key for moving forward with these technologies.
- The LH2 topic is of relevance in many nodes of the hydrogen technology chain, from bulk storage to hydrogen transportation to on-board storage for specific mobility and transport modes. This project is making an incremental step in fundamental knowledge of the problem by designing an advanced diagnostic tool and contributing considerably to expansion of the experimental dataset.
- The information sought is critical to the deployment of LH2 infrastructure for public use. Without it, hydrogen dispensing stations will be both uneconomical and unsafe. It is appropriate and perhaps critical that an organization such as SNL (unbiased) conduct the research.
- Cryogenic hydrogen is likely to be used in larger fueling stations, so the development of this information is critical. The relevance is very high for the Hydrogen and Fuel Cells Program goals and objectives.
- The project has strong relevance and potential impact toward Multi-Year Research, Development, and Demonstration Plan targets. LH2 system designs and features that can reduce the overall risk, in addition to the primary task of characterizing/modeling cold plumes and flames, should be kept in mind.
- The relevance of determining the characteristics of a plume from a liquid release might be of use in determining the appropriate setback distances. It would also be interesting to determine the lower flammability limit and lower explosive limit levels at cooler temperatures (maybe -40°C, -100°C, -150°C). Ignition energy requirements might also be of interest.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The proposed future work has been clearly defined by the project team, and the team has clearly articulated how this future work will address the remaining challenges. It is great to see that experiments and models to characterize pooling and evaporation are planned for next year.
- The proposed work is absolutely necessary, but it is still a bit general as described and needs more development/elaboration before review can determine its adequacy.
- In general, the proposed future work is appropriate and pertinent. However, the plans to address the many variables in real-world situations are not well defined.
- The proposed future work is perhaps over-ambitious when claiming to tackle real liquid spilling, including pooling and evaporation. So far, the project has focused on small-scale experiments in the laboratory.
- The proposed future work to model large-scale releases will be a significant challenge. The project team should evaluate the need and cost of large-scale releases. The team should coordinate and collaborate with others in industry to ensure success. The project should include a backup plan for model validation if large-scale releases with Raman scattering prove difficult.
- The proposed future work is limited. The team proposes to figure out the instrumentation grid, predict the extent of the plume on a release, and validate the model with data from the release. This reads as an ending

point. It should be a starting point. It would be good to know the local temperature and mole fractions in the plume, at the mole fraction at which an ignition is likely, and the pressure/thermal map of the plume at ignition, deflagration, and detonation. It is not clear how this project matches up to Chris LaFleur's work. The models should merge seamlessly.

Project strengths:

- The project pursues a good technical approach to measuring cold hydrogen gas behaviors. It is an approach that has risk, but a risk worth taking, given that previous measurement strategies have significant drawbacks. The project approach is straightforward and will directly address the needs of both equipment and standards developers.
- This project already has and will further reduce a critical knowledge gap in the field of LH2 behavior. The whole hydrogen technology chain will benefit. The project also provides advancement on basic physics as well as improvement of advanced diagnostic tools. Because of the considerable challenge ahead, including the cost of validating experiments, joining international forces is paramount. Because the project has a working interface with a parallel European project, it scores high in this dimension as well.
- One project strength is the identification of an important gap in hydrogen data, particularly cryogenic hydrogen, related to safety. Another strength is the assessment of currently available dispersion measurement techniques and laboratory use of simultaneous particle image velocimetry and Raman spectroscopy.
- Project strengths include the science-based merit, the approach and model validation strategy, the impact the project has had on national codes, and the downstream effects on the built environment.
- The project has very strong modeling and technical capabilities for LH2.
- The expertise of the laboratory is a strength.

Project weaknesses:

- There are no project weaknesses.
- The work is absolutely needed, and the results could be applied to today's development efforts. Perhaps the work could be pursued faster. Certain spill hazards could be investigated without the cold gas dispersion knowledge and therefore might be done in parallel. DOE would need to make more resources available to accelerate work.
- A milestone has already been achieved in the project regarding the diagnostic to be adopted in the following phase of the project. The choice has fallen on an advanced optical diagnostic, which is the only one promising to capture the complex processes of cryo-releases in their entirety. Nevertheless, the project also has the ambition to study scaled-up field releases (closer to real-world situations). It may be the case that the advanced diagnostic (still partially to be developed) does not perform well in a much more complex experimental set-up or that a high number of very expensive experiments will be necessary for validation. The project seems to have focused on only one diagnostic strategy, and it is not clear why the possibility to make use of standard, much less accurate but cheaper and already well-tested sensors has been excluded.
- Large-scale validation of the model will be a challenge. The project team should consider including a backup plan for model validation if full-scale LH2 system-level releases are not practicable/feasible.
- The approach of the laboratories and the lack of accessing data from other industry and government entities are weaknesses.
- The project will need to address a wide range of leak/spill situations. This should include environmental effects.

Recommendations for additions/deletions to project scope:

- There are no recommendations for additions/deletions to the project scope.
- Scope expansion recommendations would suggest accelerating work by describing in more detail what spill testing should be conducted. Experimental efforts that do not require the cold gas dispersion techniques could be pursued on a more aggressive schedule. Possible initiatives might include developing the following:

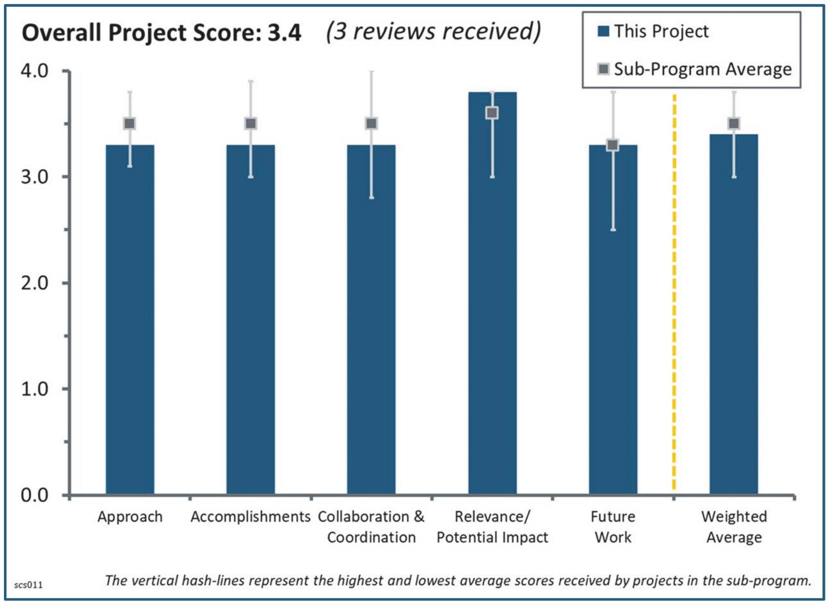
    - Interactions with ambient gases.
    - Data on pool formation and modeling how large pools can become, how long they persist, and what factors influence outcomes. This should include steady leaks that will chill the ground until a pool can persist and, under certain weather conditions, will promote advance of a ground-level cold plume that can extend some distance from the leak point.
    - Identification of circumstances that lead to shock-sensitive mixture formation and experiments to bound the likelihood of their formation.
- One recommendation is to further deepen and expand the international collaboration, in particular when going for full-scale field experiments. Another recommendation is to reconsider the diagnostic strategy to add more standard (i.e., off-the-shelf) sensing methods, as well as a benchmarking exercise.
- The team should continue to stay abreast of similar efforts in other countries, for example, in the European Union and Japan. The project has had success in modeling in a laboratory situation. Perhaps this could be relevant to potential cryogenic hydrogen use indoors, such as forklift operation in a warehouse.
- It is unclear whether NASA White Sands is a better test site. Perhaps the project could ask NASA or the Jet Propulsion Laboratory for suggestions on instrumentation.
- The project team is strongly encouraged to keep engaging with industry stakeholders that handle large volumes of LH2.

Project #SCS-011: Hydrogen Quantitative Risk Assessment

Alice Muna; Sandia National Laboratories

Brief Summary of Project:

The primary objective of this project is to provide a science and engineering basis for assessing the safety of hydrogen systems and facilitate the use of that information for revising regulations, codes, and standards (RCS) and permitting stations. Sandia National Laboratories will develop and validate hydrogen behavior physics models to address targeted gaps in knowledge, build tools to enable industry-led codes and standards revision and safety analyses, and develop hydrogen-specific quantitative risk assessment (QRA) tools and methods to support RCS decisions and to enable a performance-based design code compliance option.



Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project approach is good to ensure that safety analysis is based on validated scientific models and that such analysis is incorporated into models for usage by industry and codes organizations. The content of the approach for this year appeared to be on maintenance and support, rather than on new contributions.
- There is good coordination with other projects feeding data into this project to support this project's efforts.
- The approach is tried and true. However, some verification may be in order. It was previously suggested that the model be used to predict the requirements for a liquefied natural gas release and then compare the model's predicted separation distances with the separation distances required by National Fire Protection Agency codes. This would give an indication as to the degree of conservatism in the requirements and possibly be the ammunition to relax the distances for hydrogen.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Input into model codes makes it possible to reduce separation distances for storage at fueling stations. This is an excellent accomplishment that will make it easier to site these stations. There is progress in terms of liquid release modeling, but it must be validated with diagnostic tests.
- The overall progress is appropriate to that which is expected from a professional engineering organization. Expanding the flexibility of the model is a big plus. As an aside, the table on slide 9 needs a little work. The precision on the distances does not match the accuracy of the model. A tolerance equivalent to 1% of full scale on the appropriate gauge is sufficient.
- The accomplishments for this project were good, as depicted by the publication of the tunnel safety study, although other progress metrics needed to be further clarified. It is good that the Hydrogen Risk

Assessment Model (HyRAM) is being expanded to other applications, but examples of the other applications would have been useful. The further reduction in separation distances is excellent. Examples of HyRAM being used by hydrogen infrastructure providers in the field would be a good addition to identify the progress.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The project appears to have an excellent collaboration list including both national laboratories and industry. The project clearly is involved with codes and standards organizations and the distribution of the tools.
- There is good coordination with other national laboratories and fuel station providers; however, the project should attempt to coordinate with authorities having jurisdiction (AHJs) to find a jurisdiction that will allow the use of the risk assessment model.
- The lack of major players and of AHJs is disappointing. Having a state or major east coast city fire marshal's office (such as the New York City Fire Department [FDNY]), a utility (possibly Pacific Gas and Electric), and an energy provider (such as Exxon Mobil) would help with credibility and advertising.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The rigorous science basis of safety analysis is of high relevance and very impactful to the fuel cell electric vehicle market and commercialization. Without this and similar DOE projects, the codes and standards would not have the data and analysis for making informed decisions.
- If used properly, this tool should be useful in reducing setback distances. Buy-in from FDNY would cement the acceptance.
- The use of the risk assessment model could enable the location of fueling stations and other applications to be more easily sited. The prescriptive setback distances required by the model codes may be overly conservative, and the use of HyRAM could help overcome this burden.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The plans to expand the model for use in other applications are relevant, specifically the plans for use with liquid hydrogen applications.
- The proposed future work is good, although it could be further developed to acknowledge the remaining barriers associated with hydrogen QRA, along with identifying opportunities to validate the results and strengthening the effort with codes and standards development.
- Outreach needs to be considered to get acceptance and usage of project results.

Project strengths:

- The project strength is the coordinated effort among various DOE projects to evaluate behavior, develop methods to assess risk, and apply these procedures using models that are released to the public. The individuals on this project are also a strength in their ability to predict hydrogen behaviors to influence practical applications.
- This project's strength includes its coordination and collaboration with other projects, as well as opportunities to reduce storage and equipment setback distances. The use of the model to justify code changes is also a strength.
- The expertise of the laboratory is a strength of this project.

Project weaknesses:

- The project weakness is that the scope of the tools in the past has been focused on infrastructure. It was encouraging that there is an effort to expand the application of HyRAM.
- To utilize the model, the project proponent must find a jurisdiction that will allow the use of the model, which may be difficult. Outreach to the prospective jurisdictions where stations are to be built should be a priority in order to find a good fit.
- The limited access to the novice is a weakness of this project.

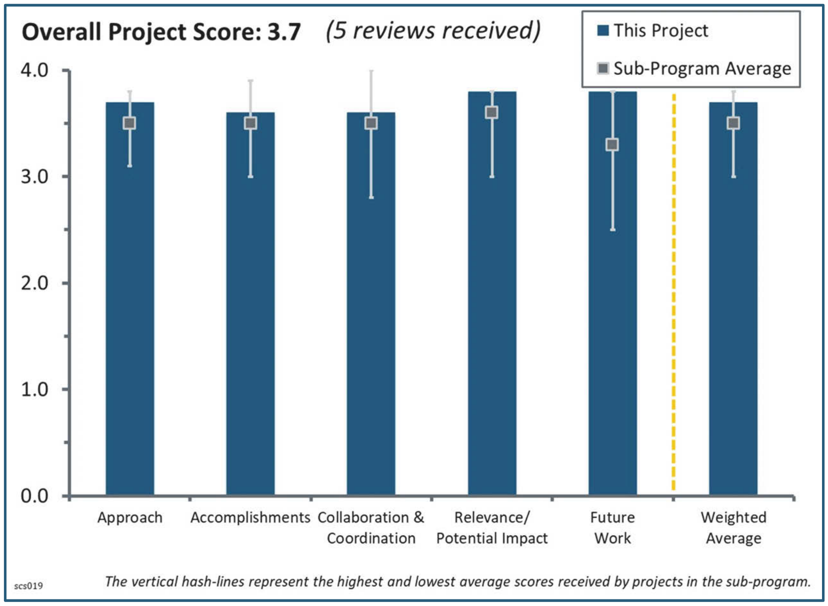
Recommendations for additions/deletions to project scope:

- It is recommended that the project continue to expand the use of HyRAM beyond infrastructure. For example, the HyRAM tool could be used for releases on a vehicle related to the thermally activated pressure relief device, especially in providing scientific guidance regarding the preferred location and orientation of the release. In addition, the emissions from the vehicle tailpipe could be further evaluated to understand the actual safety hazards.
- It is recommended that the project team focus more on federal and state collaboration. It is important to get buy-in from fire marshals and thus, general access of the general public through the marshals.

Project #SCS-019: Hydrogen Safety Panel, Safety Knowledge Tools, and First Responder Training Resources

Nick Barilo; Pacific Northwest National Laboratory

Brief Summary of Project:



This project provides expertise and recommendations through the Hydrogen Safety Panel (HSP) to identify safety-related technical data gaps, best practices, and lessons learned, as well as help integrate safety planning into funded projects. Data from hydrogen incidents and near-misses are captured and added to the growing knowledge base of hydrogen experience to share with the hydrogen community, with the goal of preventing safety events from occurring in the future. The project also aims to implement a national hydrogen emergency response training resource program with adaptable, downloadable materials for first responders and training organizations.

Question 1: Approach to performing the work

This project was rated **3.7** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This project is really twofold—the HSP and safety outreach. The approach to both is excellent. The Hydrogen Tools (H_2Tools) portal is becoming an ever-increasingly valuable tool nationally and internationally. Indeed, the international community is turning to the portal as a single point for dissemination of lessons learned, archived papers from the International Conference on Hydrogen Safety (ICHS), etc. The H_2Tools portal is an incredibly valuable resource. The HSP needs to grow and change its focus to be in line with the maturing and changing hydrogen landscape. The emerging collaboration/ partnership/cooperation with the American Institute of Chemical Engineers (AIChE) at this point is perfect. That expanded platform very well could be exactly what is needed for continued and expanded value added for the HSP.
- This project is making excellent use of unique and specialized expertise available in the U.S. Department of Energy (DOE) and the national laboratories to ensure that markets are ready with critical safety and emergency information for expanding hydrogen use into their jurisdictions. The approach has a keen eye to ensuring that the work is not one-time-use and instead provides a growing library of insights and lessons learned as more experience is gained. This aspect of the approach is critical and exemplary.
- Three projects are in the report. The first is the activities of the HSP. The second is the safety knowledge tools. The third is first responder training resources. The approach, as described in the presentation, is appropriate to the funding. Identifying that input into the design, and to a lesser extent construction, is the most technically appropriate and cost-effective approach—in retrospect, an obvious finding. Companies have found that using a tool called a hazard analysis, a top-down discussion to identify and quantify the issues, at the start of a project is helpful. Annex A in American National Standards Institute/Canadian Standards Association (ANSI/CSA) FC 1-2014, "Fuel cell technologies – Part 3-100: Stationary fuel cell power systems – Safety" has a fairly extensive, but not exclusive, list of potential hazards that might be used to populate a hazard analysis. At the end of the design phase, a bottom-up assessment is made, which

often results in changes before construction. The tool often used on a product is a failure mode and effects analysis. The tool often used on a process is a hazard and operability study. Both tools evaluate the effects of a single point of failure (cascade failures are considered single point). This analysis method is used to identify where multiple levels of safety are needed to avoid serious incidents.
- The approach is excellent. Now the project needs extra funding to increase availability for safety reviews of a large number of projects.
- The project objectives are clearly matched with DOE goals. The project has three distinct tasks, all of which are integrated well into other relevant efforts.

Question 2: Accomplishments and progress

This project was rated **3.6** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This project is really the collection of three different activities: (1) HSP, (2) first responder training, and (3) outreach. This principal investigator and this project have excelled in each of these areas in the following ways.
    - The HSP has gained international recognition to the point that the European Union has emulated this and started its own HSP activity. The HSP has grown beyond its historical activities focusing on providing reviews and safety assistance to the DOE projects. Engaging with California and providing safety reviews and assistance to HSP rollout in California is an excellent example of a very successful extension of the HSP traditional engagements. The engagement with the AIChE should prove to be an excellent move forward for the HSP.
    - First responder training remains a hallmark of this overall activity. Collaborating/coordinating with the California Fuel Cell Partnership has been and remains excellent leveraging of activities. A lack of understanding that training must go beyond the bounds of just those that have hydrogen projects in the local jurisdiction is starting to become an issue. Several examples exist in which first responder training in the jurisdiction with the hydrogen project was performed appropriately, but upper management changed, the new management did not get trained, and an incident occurred. The untrained individual had authority, resulting in over-reaction. The potential new relationship with AIChE in this space and the creation of a “Center for Hydrogen Safety” is probably perfectly suited to expand the hydrogen first responder training to a much broader audience and not just those with hydrogen projects in their jurisdictions, which is outstanding.
    - The H_2Tools portal continues to grow and prove itself as an international resource. Other safety and regulations, codes, and standards organizations not only use the portal but are now contributing to its content. Examples include the International Association for Hydrogen Safety, ICHS (paper portal), and the Japanese. The International Partnership for Hydrogen and Fuel Cells in the Economy just agreed to use the portal as a central dissemination point for “lessons learned” and information with a safety focus to disseminate to the public, which is outstanding.
- The Center for Hydrogen Safety effort represents excellent progress. Significant accomplishments and progress may lead to understaffing due to the need for availability.
- The project appears to be addressing the safety and emergency response needs in a significant number of markets and areas and appears to be focusing relative amounts of effort appropriately with the pace of development of hydrogen initiatives in each respective region. It is good to see the focus expanding to the Northeast states as their network efforts grow alongside California’s. The project identified a need to expand its reach beyond just the particular jurisdictions that contain hydrogen fueling locations, to all jurisdictions where hydrogen customers may travel with that hydrogen. This is a very well-identified need and should be a priority. At the moment, the question of how to accomplish this has not been answered, but it should be a priority for the coming year(s).
- The accomplishments still appear to be California-centered. The limited expansion into Connecticut, another progressive yet different environment (distributed jurisdiction versus central, professional jurisdiction) is wise. Expanding this to include New York City (Fire Department of New York City) should be a goal. Expanding into South Africa may not be a wise move based on the instability of the region. Focusing on areas of high fuel costs and high pollution issues may be more cost-effective. Examples for consideration include Italy, Poland, India, and Mexico. Outreach through the transit agencies and trade

organization(s) might be useful. Perhaps discussions with the U.S. Department of Transportation (DOT) Federal Railroad Administration (FRA), Amtrak, Metro-North Railroad, New Jersey Transit, etc. would be useful, if discussions are not already ongoing. Permission to transport hydrogen through rail tunnels by FRA might help deal with the Port Authority of New York & New Jersey (the Port Authority). Additionally, these authorities may be interested in clean electric locomotives that can run on non-electrified tracks. In the Amtrak Northeast Corridor, trains from Boston to Washington, DC, are electrified (and have been so for over 100 years). However, most of the feeder lines are not. The use of hydrogen fuel cell locomotives can "electrify" the rails to at least Roanoke and Newport News, as well as the inland route (Hartford, Springfield, Boston), Philadelphia, Maryland Area Regional Commuter (MARC), Virginia Railway Express (VRE), etc. The white papers written sound interesting, but it is not clear how to obtain them.
- There is a backlog of HSP reviews to complete and still much work to ensure that first responders are ready to appropriately handle an incident at a hydrogen fueling station, other hydrogen facility, on a highway, etc. The project is well designed to work toward these ends; however, progress was slowed because of funding constraints during the first half of the fiscal year.

Question 3: Collaboration and coordination

This project was rated **3.6** for its collaboration and coordination with other institutions.

- The new collaboration with AIChE to establish a Center for Hydrogen Safety is a notable development. This will help ensure hydrogen safety information and tools are readily available to chemical engineering professionals. It is a significant step toward rolling out the hydrogen safety work beyond the hydrogen community. Many of the key organizations are engaged in the work. The support of HSP members is critical. Building upon the new effort with AIChE, future collaboration with well-known entities that supply training to a wider variety of professionals will further the effort to roll out the knowledge beyond the hydrogen community.
- The aggressive outreach by Pacific Northwest National Laboratory (PNNL) clearly shows in the impressive list of collaborators: national laboratories, industry, standards development organizations, code development organizations, other special interest organizations, etc. All contribute to the success of this project.
- The list of project partners involved is comprehensive and has the right mix of collaborators. Their collective work appears to be effective and leverages their respective strengths well.
- The collaboration and coordination is excellent, including the global institutions.
- The collaboration with different organizations should be evolving with time. PNNL should be ultimately supporting public safety agencies such as DOT FRA, Amtrak, DOT Pipeline and Hazardous Materials Safety Administration (PHMSA), and the Coast Guard. PNNL projects should be moving toward that goal with focus on all alternative fuels. The project should work toward being the testing and training support for PHMSA, the Coast Guard, and the various state agencies.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- All three elements of this project are critically important to help ensure the safe deployment of hydrogen technologies, with the accompanying first responder training to help ensure that when events occur, they are handled in the safest manner possible.
- Put simply, this work is absolutely necessary and mission-critical.
- All three topics are highly relevant. The project should be careful to avoid overreach. PNNL should support testing and training support at PHMSA, the Coast Guard, and the various state agencies. PNNL should not usurp the code authorities or the Nationally Recognized Testing Laboratories (NRTLs). Outreach to DOT FRA, Amtrak, and the Northeast commuter railroads might help with the Port Authority.

- The project has high impact owing to progress around the world and the steep learning curve for new entrants in the market.
- All three aspects of this project are directly relevant to multiple DOE objectives.

Question 5: Proposed future work

This project was rated **3.8** for its proposed future work.

- All three efforts have worthwhile plans for future activities. Continuation of the HSP and discussions in the Northeast are excellent endeavors. The advancement of collaboration with AIChE to establish a Center for Hydrogen Safety is a notable activity. It is a significant step toward rolling out the hydrogen safety work beyond the hydrogen community. Further, future collaboration with well-known entities that supply training to a wider variety of professionals will further the effort to roll out the knowledge beyond the hydrogen community. Putting props in the hands of the Massachusetts Fire Academy is good. The plans are very promising. It is to be hoped that resources are sufficient to get it all done.
- The value to the safe deployment of hydrogen technologies into the commercial environment has been clearly demonstrated. The articulated future plans are on track to continue and improve on this excellent track record. The collaboration with AIChE should prove to be a powerful step in the right direction for this work.
- The proposed work is appropriate. Outreach to other NRTLs versed in products in this field (FM Approvals LLC and Intertek Testing Services NA, Inc.) may be of benefit to all. Outreach to supply research and training support to federal, state, and local officials who have authority in this area is a must. However, the offer should not be limited to hydrogen but rather should extend to all transportation and transported fuels. Comparisons of hydrogen properties to methane, propane, pentane, and acetylene (i.e., fuels to which the authorities having jurisdiction [AHJ] are well accustomed), using data from Perry's and National Fire Protection Association 497 (i.e., references the AHJs use and trust), have worked very well with AHJs in Connecticut in the past.
- The presentation noted the wide reach of the tools that are available online and the continuing effort to keep information up to date. As more information continues to be developed through this effort and available to stakeholders across the world, there may need to be increasing focus placed on organization of the information for those visiting the online data websites. There may also need to be a "customer-focused" approach adopted for guiding visitors with varying degrees of familiarity with hydrogen to the appropriate information.
- The project team should consider growing/expanding collaboration with different departments within DOT that touch on safety aspects of hydrogen and fuel cell vehicles (all applications) to provide reliable resources and education in this topic area.

Project strengths:

- This project does an outstanding job at providing (1) a safety tools portal for the international community, (2) much-needed first responder training (and an expanded audience of those exposed to this training, thanks to the new relationship with AIChE), and 3) the HSP, which has proven to be a well-recognized, internationally valuable activity that is being replicated elsewhere internationally. The partnership with AIChE should enhance this capability, which is outstanding.
- The three activities strongly support DOE goals and are well coordinated with each other and other projects funded by DOE. The project is beginning to address legacy issues by establishing relationships with others to expand the effectiveness of this effort.
- The project is essential in the effort to provide a balanced view of all safety aspects involved in hydrogen and fuel cell vehicle technology. First responders and stakeholders need reliable and consistent information to be able to provide an acceptable level of safety.
- The project's strengths are its relevance and its necessity. In addition, it is well organized and is particularly effective at disseminating highly valuable information to a wide audience.
- The expertise of the laboratory is a project strength.

Project weaknesses:

- The HSP has expanded its role beyond its historical activities of reviewing the DOE projects, which has been an area for comments and encouragement from the Hydrogen and Fuel Cells Program Annual Merit Review over the past few years. Funding continues to be a challenge for this important and well-respected activity. The H_2Tools portal is, and has proven itself to be, an international resource, both as a resource and as a depository for international communication (e.g., ICHS papers, international incidents, etc.). Again, this project is financially challenged.
- The project's limited budget is probably its biggest weakness. There is much more work to be done than is budgeted.
- This work is very important, and there is still so much more to do faster. It is not clear that resources are sufficient.
- The parochial approach of the national laboratories is a weakness that, it is to be hoped, will change.
- The lack of a secured funding stream for the Center for Hydrogen Safety is a weakness.

Recommendations for additions/deletions to project scope:

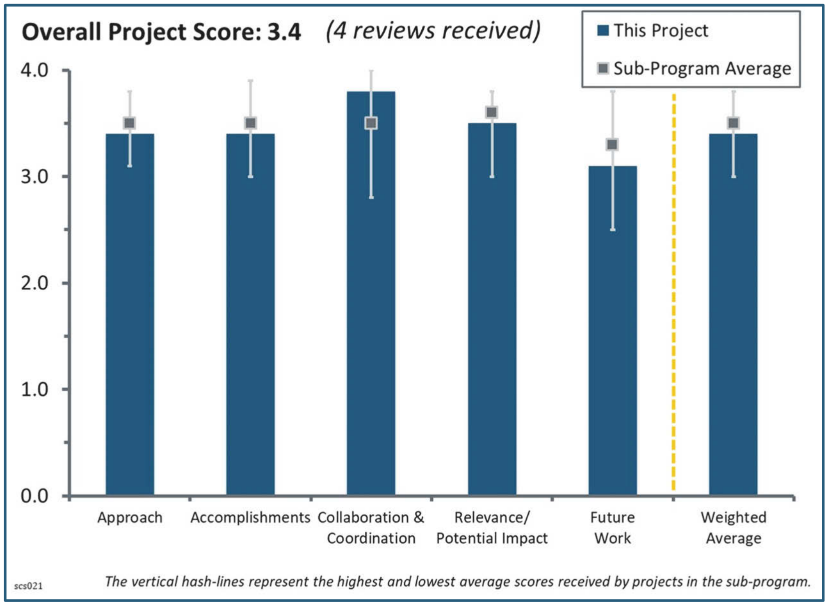
- There are no recommendations for additions/deletions. The project is on the right path.
- The issue of resources for planned future work should be addressed. Rolling out the learnings to others is a necessary step to maximize impact of the work and to train professionals to perform project safety reviews, particularly as the number of deployments grows beyond the ability of the HSP to review them all in a timely fashion. There may be others, particularly entities who train emergency responders, engineers, and other professionals, that can be identified to build upon the AIChE idea.
- There is a need to expand the project's reach beyond just the particular jurisdictions that contain hydrogen fueling locations to all jurisdictions where hydrogen customers may travel with that hydrogen. This is a very well-identified need and should be a priority. At the moment, the question of how to accomplish this has not been answered, but it should be a priority for the coming year(s). In addition, the upcoming partnership with AIChE likely will go a long way toward this, but the project seems like it needs to develop a clearer path for transfer of the work and effort (or simply the funding support) to another body, given the limited DOE funds that are allocated.
- The project should focus more on federal and state collaboration and less on being seen as the model code experts. The AHJs are the decision makers, even when they are not hydrogen experts.

Project #SCS-021: National Renewable Energy Laboratory Hydrogen Sensor Testing Laboratory

William Buttner; National Renewable Energy Laboratory

Brief Summary of Project:

Sensors are a critical hydrogen safety element and will facilitate the safe implementation of the hydrogen infrastructure. The National Renewable Energy Laboratory Sensor Testing Laboratory tests and verifies sensor performance for manufacturers, developers, end users, and standards-developing organizations. The project also helps develop guidelines and protocols for the application of hydrogen safety sensors.



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach is thorough and well developed. There is a progression of the technological aspects of hydrogen sensors from assessment toward practical deployment. A strong collaborative network has added to both the richness of the findings and the use of the work produced.
- This is an ongoing activity with clearly articulated motivations, goals, and objectives. The project continues to be well executed and well integrated into other efforts, including those done internationally.
- The most effective portion of this effort relates to the team's determination of which sensor was best for a given application and how to locate it.
- The approach is basically for the project to act as a resource for the hydrogen community through the use of laboratory assessments, field deployments, and partnerships. While this is good and very useful to the hydrogen community, the presentation did not really address how the project accomplished the objectives. The project appears to be mainly reactive to needs as they arise.

Question 2: Accomplishments and progress

This project was rated **3.4** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This principal investigator (PI) maintains a fairly high level of excellent quality publications, presentations, and reports detailing the results of this project. This guarantees timely dissemination of this effort to the community to ensure the safe deployment of hydrogen systems. This project received special recognition from the DOE Office of Energy Efficiency and Renewable Energy as a success story for the involvement with KPA Services, LLC (KPA) and Toyota Motors in permitting fuel cell electric vehicle repair facilities—this is outstanding. The outdoor cold hydrogen plume used sensors multiplexed together into an array that was simplistic and criticized as a result. Nonetheless, it did answer some critical questions, such as whether hydrogen reached the ground under these conditions—the answer proved to be yes. This was a question in need of answering by the National Fire Protection Agency (NFPA) code committee. This system has been greatly improved by the implementation of many sensors that can be operated in parallel, rather than in series. Also, the development of validation system optical techniques, such as light detection and ranging (LiDAR), is in progress. This is outstanding.

- Significant progress has been made, but work to improve the clarity of the project's objectives and performance indicators would result in a higher score here; the accomplishments contribute to overcoming some barriers. As an example, the project mentions SAE standard J3089: Characterization of On-Board Vehicular Hydrogen Sensors. It is worth noting that the PI led this effort to develop the technical information report (TIR) at SAE. This TIR is undergoing ballot, and it appears to be very well received by industry. This activity directly supports the project's approach of developing strategic partnerships to support the deployment of hydrogen sensors. This seems to specifically contribute to DOE Objective G, which states that there is "Insufficient technical data to revise standards."
- The project has produced accomplishments. Practical limitations in the efficacy of available products in the market have been assessed and analyzed. Both laboratory and field efforts have been productive in assessing the use of sensor technology. The publication of a reference book on hydrogen sensors and the 2017 workshop report are positive tangible outcomes for the community. Frequent citing of papers reinforces the relevance of the findings. Work with the European Commission Joint Research Centre (JRC) and the activities supporting the development of the global technical requirements in GTR-13 also reinforce global reach. The present work to identify how sensors may be used to effectively change the NFPA 2 standard for the Hydrogen Technologies Code and reduce clearances is promising in advancing practical siting of hydrogen stations. However, there is a need for additional clarity and alignment with the findings of the work by Ethan Hecht et al. from Sandia National Laboratories (SNL) (R&D for Safety, Codes and Standards: Hydrogen Behavior), which concludes that sensors will not be effective because of their limitations and that optical technologies are more practical. More clarity going forward as it relates to the sensor laboratory, coordination for gaseous and liquid applications, and co-optimizing the work on each project being applied practically would be beneficial.
- The sensor evaluation provided results that indicated that some sensors were not performing as required. It is unclear whether feedback was supplied to the sensor manufacturer, but if not, this information should be provided.

Question 3: Collaboration and coordination

This project was rated **3.8** for its collaboration and coordination with other institutions.

- This project has a history of mentoring young scientists and engineers, providing a unique learning experience. The collection of collaborators is impressive. More important is the long-standing collaboration/cooperation with a parallel facility at the JRC in Petten (the Netherlands); also upcoming are collaborations with the Health & Safety Laboratory and others on the development of a hydrogen wide-area monitor (HyWAM) system, which is critically needed to understand leak origins and dispersion.
- Collaboration has taken many forms and is robust and rich. The relationship with JRC has leveraged strengths from each institution and expanded global relevance. The sensor workshop engaged the broader technical community effectively, and the report captured relevant information on gaps to be addressed. Field work with KPA and Toyota has addressed practical market uses of sensor technology and leveraged field experience. Work with the U.S. Department of Transportation has helped address both vehicular and infrastructure applications of sensor technology. Work with SNL needs to be better coordinated for a clearer message to the community about the relative merits and limitations of different technologies in particular applications.
- The project team seems to be collaborating with all the right stakeholders and appears to be readily available to expand collaborations as needed.
- This project has some excellent collaborations with industry and other government entities.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project aligns well with the Hydrogen and Fuel Cell Program's (the Program's) priorities on safe deployment, and the project has helped advance knowledge on the use of sensors to promote the safe use of hydrogen technologies. Relevance across vehicular and infrastructure applications has been considered and addressed. Advancing the understanding of the efficacy of available sensors has reinforced both the confidence in the project's potential and the need for a better systemic validation of efficacy. Future impacts for H2@Scale (through HyWAM) and NFPA 2 siting requirements might be promising potential impacts, but both would need to be better aligned.
- Sensors are required by the codes. Understanding sensor behavior, being able to select the correct sensor, and determining its appropriate placement is critical to (1) being able to detect hazardous leak events and (2) understanding hydrogen release behavior. These techniques are applied in very expensive laboratory environments, but application in the field is critical.
- The project is relevant because it applies science to help solve safety needs through improved sensor performance and application. The development of a TIR at SAE will improve the impact of the work in vehicles; meanwhile, work on the HyWAM system has the potential to improve the impact for hydrogen fueling stations and other facilities.
- While the sensor location and type of sensor to be used is relevant, there are existing sensors available that can meet necessary requirements.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- Future work on using findings to address sensor placement and optimize hydrogen station specifications is relevant. Considering applying the findings for H2@Scale is also relevant. Field testing of exhaust gas analyzers is a logical progression. More details around the execution of these aspects would be helpful in promoting success.
- The proposed future direction is appropriate for this work. The focus on the development of a cost-effective radially deployable HyWAM is encouraging. Point measurements are necessary at times (strategically located to indicate a hazardous condition resulting from a leak); however, they are flawed in that one cannot be assured that they are indeed providing the appropriate information. The leak and dispersion of a hazardous cloud may never reach the sensor geographically or temporally to mitigate the hazard. A HyWAM does not have this limitation. The HyWAM will be very valuable in identifying a leak and the resulting plume location.
- HyWAM, sensor placement, and process control activities are good next steps.
- While the work on the wide-area network is interesting, there are no existing sensors of this type, and it may not be practical to initiate work on this. More emphasis on sensor location would be preferable.

Project strengths:

- This project continues to produce high-quality, relevant results in evaluating sensors and developing new capabilities to answer challenging questions posed by those who need answers, such as the code committees, global technical regulation working groups, etc. It is particularly encouraging that this PI has engaged with the SNL Combustion Research Facility (CRF) regarding their detailed plume modeling of cold releases from hydrogen. This will prove to be very valuable in validating the plume release single-point measurements.
- Project strengths include relevant accomplishments, a strong collaborative network, sustained engagement of the technical community, and a good progression of findings to practical scale, even with funding reductions in fiscal year 2017.

- The PI is clearly a national leader in sensor technologies—leading the effort to publish a TIR for SAE is a major achievement. The HyWAM work looks very promising.
- The project's strengths lie in its evaluation of the sensor's location and the type of sensor used for a given application.

Project weaknesses:

- Reaching out to engage the talents of others (such as the CRF) removed the only concern, which was expressed in previous Program Annual Merit Reviews. There are no weaknesses.
- The main weakness is the need for improved clarity with the SNL findings for stations, which should be addressed. There will be an opportunity for a more holistic and consistent approach to be articulated. The next (2020) edition of NFPA 2 is in the Annual 2019 Revision Cycle, which is in progress. Since revised setback distance is an important practical outcome of the project, and "Insufficient technical data to revise standards" is one of the identified barriers the work has intended to address, clearer articulation of the specific outcome(s) would be beneficial. As more start to rely on sensors based in part on this project, additional work to understand and characterize sensor degradation and ongoing efficacy will be important in maintaining the safety of the systems over their useful lives. It would be helpful to refresh the applicability of the data management plan to the details of the project.
- Some of the sensor evaluation work seems to be something that an entity such as Underwriters Laboratories (UL) could perform and, therefore, seems not to require DOE funding. Sensor manufacturers should seek a listing for their products to a published standard.
- There was no data management plan. There is no information provided to facilitate access to the research.

Recommendations for additions/deletions to project scope:

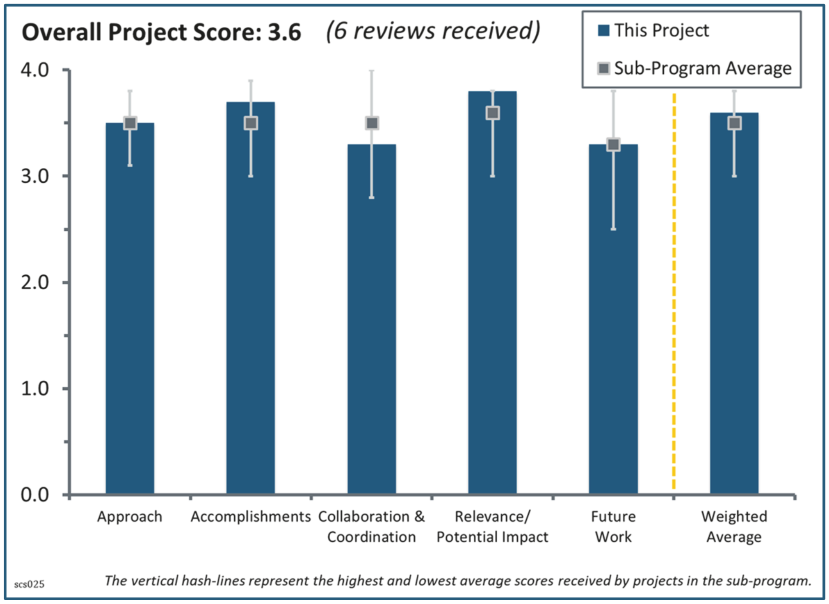
- The clarification of sensor uses versus optical detector uses will be important. Work to address sensor degradation/poisoning modes and to characterize efficacy over the lifetime will be important for effective and ongoing safety of the systems in use that rely on sensors.
- The engagement of detailed cold plume modeling is supported, as is the continuation of powerful collaborations (particularly with the JRC) and the development of the HyWAM.
- It is recommended that the team consider adding a method for accessing the project data, reports, presentations, draft plans, etc. The team should ensure these can be readily accessed by stakeholders.
- If sensor testing could be done by UL or a similar entity, it could be removed from the project scope.

Project #SCS-025: Enabling Hydrogen Infrastructure through Science-Based Codes and Standards

Chris LaFleur; Sandia National Laboratories

Brief Summary of Project:

The goal of this project is to enable the growth of hydrogen infrastructure through science- and engineering-based codes and standards (C&S). Specific objectives include (1) streamlining cost and time for station permitting by demonstrating alternative approaches to code compliance and (2) revising and updating C&S that address critical limitations to station implementation.



Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project team is doing a good job of using analysis to select/develop experimental methods for the liquid hydrogen (LH2) separation distance modeling. Likewise, for the tunnel behavior modeling, the project has executed a couple of specific scenarios for specific Boston tunnels and is now looking at a holistic approach that could be applied more generally.
- This is one of the most productive and important projects that the U.S. Department of Energy (DOE) funds, as it is greatly helping code development. It also is an integral support to the safety community.
- This effort is imperative to the successful deployment of hydrogen infrastructure.
- The project appears to build on its successful approach from past years.
- The approach on some barriers is very strong, for example, the technical data attempts to revise C&S and create a synchronization between codes and standards. The approach could be improved by undertaking alternate methods to address code compliance and usage/access restrictions in tunnel parking structures.
- The work being performed is critical, but it may not be sufficient to achieve end goals. The work's focus was on the effects of the hydrogen flame to the tunnel structures. While this is critical, something should be said about the hazards to other vehicles and drivers, as well as the effect of other fuel fires upon the hydrogen vehicle. This may be an expanded scope. The effort does identify the need to communicate with tunnel authorities, but no such specific authorities are listed as part of the collaboration. A separate comment is that the presentation seemed to have a dual focus—partially to review the total coordinated activities and partially to review the technical advances in tunnel hazard research. With regard to the other Sandia National Laboratories presentations that referenced their role in the total coordinated activity, there seemed to be an inconsistent approach. Perhaps a separate project presentation should cover how C&S research was addressed overall and present specific technical investigations separately.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The tunnel project has delivered outstanding results and demonstrated that it can satisfy the requirements of the engineers in the authorities having jurisdiction (AHJs), if not the bureaucrats. The LH2/cold leak project is doing a good job of working through significant technical challenges in measuring the cold plume and is making good progress.
- The project has made progress in working with code officials/regulators to understand and address regulatory barriers.
- In general, the C&S effort has identified primary barriers and is systematically addressing them (which is excellent). Regarding the tunnel research, the work is vital, but it will need to focus on other aspects (i.e., a "good" rating), such as collaborating with tunnel AHJs.
- Significant progress has been made in all areas. However, more progress should be made in demonstrating alternate methods/approaches to code compliance. It is recognized that this is strongly limited by support from industry partners; however, the approach itself does affect progress.
- Excellent progress was reported, with many important milestones being met in 2017 and 2018. However, performance-based design for a real-world station seems to be progressing a little more slowly.
- The work thus far is excellent. However, it needs more support to meet some of the timelines for the code development.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- In general, this project's collaboration and coordination with institutions is strong, especially in the area of C&S synchronization and technical, science-based data for the purposes of revising C&S. Quantitative risk assessment (QRA) methods and tools have not been widely adopted by industry or recognized/understood by local authorities. The tools are available and generally easy to use, but there is a reluctance to use them as alternate methods of demonstrating code compliance in industry. The proposed future work with QRA, alongside an industry partner (FirstElement Fuel, Inc.), is a promising addition to the project and may have a significant impact on this barrier to deployment.
- The project exhibits excellent collaboration and coordination with industry partners, international organizations, national laboratories, U.S. government organizations (such as the DOE Hydrogen Safety Panel and the U.S. Department of Transportation [DOT]), and C&S organizations.
- The project has involved multiple collaborations with industry, other national laboratories, and AHJs and has also coordinated with other projects.
- The collaboration is *key* to this project's success; it is recommended the team be open to new opportunities for collaboration as they arise.
- The project is collaborating with industry partners (FirstElement Fuel, Inc., the Linde Group, and HySafe), C&S developers (National Fire Protection Association 2/55 and state transportation departments), and international collaborators (HySafe and the Prenormative Research for Safe Use of Liquid Hydrogen activity); this collaboration is important. The project team should consider whether additional collaboration is necessary, as having other station/fuel providers could help.
- Collaboration with AHJs is recognized as important, but this should not be left for later. A separate comment is in regard to the phrase "alternate means." According to the presenter, this does not refer to use of performance specifications, but the description of what was intended is not clear. The alternate means approach would require endorsement by AHJs and should be presented to them. The team should clarify whether more involvement with DOT is necessary.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is highly relevant and has a made a significant impact on the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan targets, specifically the reduction of gaseous storage separation distances through science-based code development. The project could also potentially have future effects on fuel cost reduction targets by enabling the wider adoption of liquefied hydrogen delivery to fueling stations.
- The project is absolutely relevant. The key to successful deployment of fuel cell electric vehicles (FCEVs) is in reliable and appropriate infrastructure. Meeting code requirements with alternative and safe infrastructure is necessary. Science can be used to predict and demonstrate safety parameters for tunnels and stations.
- The project has extremely high relevance and potential impact on the speed/cost of permitting the installation of hydrogen stations and facilities. This work also has relevance in “normalizing” the use of facilities such as tunnels, bridges, service facilities, and parking garages by hydrogen-fueled vehicles.
- This effort is crucial to the use and adoption of hydrogen for vehicles and to avoiding the unnecessarily conservative quantity–distance (Q-D) guidelines of the past.
- The work on both storage code improvements and modeling and tunnel research is critical and must be supported.
- This work is imperative to the progress of the hydrogen economy.

Question 5: Proposed future work

This project was rated **3.3** for its proposed future work.

- The proposed future work is promising and clearly defined. If QRA is not widely adopted by industry or accepted by local authorities, it is suggested that the team investigate alternate or backup approaches toward achieving targets.
- The plans for the remainder of fiscal year (FY) 2018, FY 2019, and beyond are concrete, well-thought-out, and aligned with the overall objectives.
- The proposed future work is defined adequately. The tunnel results of the “risk and modeling” should include a comparison of FCEVs to internal combustion engine vehicles. Sadly, the biggest obstacle may be a stubborn AHJ.
- The project has clear challenges to work on. Some invention is required for the LH2 release measurements, so it is not 100% clear whether there are alternate approaches already identified if the current approaches do not work. The work plan for the alternative methods part of the project could be clearer.
- Bringing in AHJs for tunnel jurisdictions is important. More interaction with the DOT is missing. The team needs to elaborate on an alternate means for LH2 station permits.

Project strengths:

- The project team used an effective, science-based approach to C&S development that has made a significant impact toward the deployment of hydrogen fueling stations and hydrogen-fuel-cell-powered vehicles. The project is clearly defined, with a concise objective and barriers to address.
- The project’s main strengths lie in its systematic identification of barriers to hydrogen use, research to provide information to overcome the barriers, and coordination of the use of the data in C&S. These are all accomplishments, especially in today’s funding environment.
- The project team’s past record of accomplishments is excellent, including the first part of FY 2018. The approach builds on previous years and is still very appropriate. The project is key to DOE’s goals and objectives for fuel cells and hydrogen use.
- The project’s strength is that science can be used to support the data gaps. The team possesses strong technical knowledge of C&S related to separation distances and the tunnel work.

- The project team has clearly communicated the goals and results (and needs) widely within the hydrogen community and has involved key collaborators throughout the project.
- This project provides excellent data to the code development process, and experts are available for outreach and education to AHJs. This project contains valuable input for code committees.

Project weaknesses:

- In the case of the tunnel research and modeling, the risk analysis shows that the probability of immediate ignition is not that significantly different from delayed ignition (i.e., both have low probability), while the detailed heat transfer model really addresses only the effects of heat on the structure, not overpressure or impulse from a delayed ignition or deflagration flame front. Delayed ignition and pressure are noteworthy hazards of hydrogen that are not as critical with diesel fuel, for example. These effects are important to understand for tunnels and parking structures. More justification should be provided on the decision to focus only on a heat transfer model.
- There are many excellent technical efforts being undertaken, but the framework or overarching strategy needs to be clearer so that the milestones can be more clearly tied to specific identified gaps in C&S and be prioritized to fill the most critical of those gaps.
- The tunnel work requires more technical work surrounding the effects on drivers and the interactions between different fuel hazards. As an example of a possible recent issue, NASA work shows that small combustions of hydrogen at close range can present an acoustic hazard (hearing). Perhaps the team could look into what occurs when larger quantities of hydrogen combust in the confined space of a tunnel. More explanation is necessary to make clear what the "alternate means" are.
- To continue implementing FCEV deployment, educating the AHJs on the safety of hydrogen vehicle technology is imperative to overcoming some obstacles. The team should use resources such as the Hydrogen Safety Panel to help communicate the message. It is also recommended that the team publish the tunnel risk modeling, along with a comparison of today's gasoline/diesel vehicles.
- It may be difficult and/or expensive to validate the proposed models with real-world experiments and data. Funding may not be available in the out-years. This is not necessarily a project weakness, but having to deal with multiple AHJs for tunnel safety may be difficult.

Recommendations for additions/deletions to project scope:

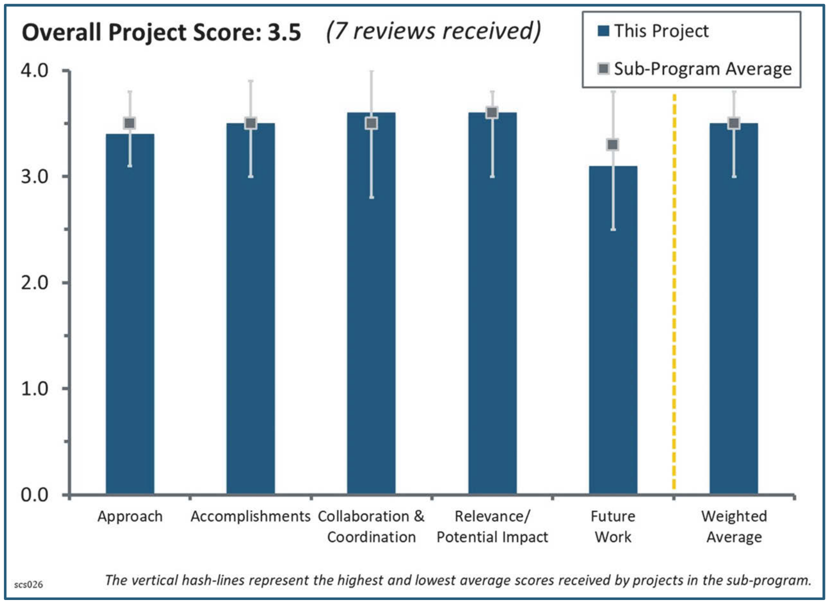
- It is recommended that the team create a matrix of specific C&S that are key enablers for hydrogen fueling infrastructure and then fill in the specific gaps for each, prioritizing the gaps so that the projects and work can be specifically targeted at the highest priorities. The principal investigator may be able to articulate this, but it is not entirely clear in the presentation, and since this is such an important area of work, it would be helpful to have a one-page format to support the Safety, Codes and Standards sub-program education and outreach process.
- It is suggested that the team consider or review the value of a performance-based design approach to alternate methods of code compliance using QRA versus other approaches or methods of demonstrating code compliance, such as alternate materials and methods justifications.
- It is recommended that the team accelerate work on bringing tunnel AHJs into the discussion of tunnel safety. The project team should also further elaborate how alternative means analysis would work.
- The team should address, in more detail, the need to develop/obtain sufficient technical data to revise standards.
- The project should model the comparison of other fuels and their reaction in tunnels.

Project #SCS-026: Compatibility of Polymeric Materials Used in the Hydrogen Infrastructure

Kevin Simmons; Pacific Northwest National Laboratory

Brief Summary of Project:

The project objective is to fill a critical knowledge gap in polymer performance in hydrogen environments. Investigators are gathering and assessing stakeholder input about the challenges, materials, and conditions of interest for hydrogen compatibility. Findings inform the project's development of standard test protocols for evaluating polymer compatibility with high-pressure hydrogen, characterization of polymers, and development and implementation of an approach for disseminating the information.



Question 1: Approach to performing the work

This project was rated **3.4** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The approach is good: gather industry stakeholder input, followed by failure mode and effects analysis, to prioritize the concerns needing more work. The translation of these priorities into fundamental tests represents an excellent approach—those tests can be used to build the database or as a launching pad for other organizations/companies to do comparative testing of other materials. It would be useful to do some vetting of test methods to make sure they encompass real-world geometries (such as O-rings) and applications (such as air on one side and hydrogen on the other).
- The approach to the work is appropriate; the team employs performance-based methods and utilizes codes and standards development organizations as a mechanism for the ultimate delivery of outcomes. As this is potentially the last year of this project, it is appropriate that the gas pedal has been hit with the standards organization. It is good to hear that progress on the development of the CSA's Compressed Hydrogen Material Compatibility 2 (CHMC 2) document is moving forward nicely.
- The approach constitutes a disciplined development of characterizing material compatibility for polymers used in hydrogen systems. The use of test environments and characterization methods has resulted in practical tools that have been and will be disseminated to the technical community to guide optimal designs and selection of materials for safety and performance.
- The approach to this work is well focused and clearly outlines well-defined opportunities.
- The approach is excellent. The compounds selected are relevant and in current use. The involvement of the Parker O-ring division would have been preferred. UTC Fuel Cells used Parker O-rings for the Apollo and Space Shuttle programs.
- There is a significant lack of clarity in the objective and purpose of the work. The specific stated objectives and overall presentation raise the question of whether the project is developing test methods, investigating industry component failures, or characterizing polymers for the proposed database. There seems to be a huge disconnect between the scientific motivations for this work and the industry need for test methods and component failure data. The approach for the test method development was not discussed. The approach for the basic research on polymer characterization did not explain what scientific gaps were being addressed by this research. The approach for disseminating relevant information was not discussed. The project also does not appear to address Barrier J in any meaningful way.

- The project is all about experimental observations and data collection. There is no underlying science; hence, the project contains only material- and design-specific results. The testing protocols that were developed and will be developed have no underlying science to make them universal. In fact, because of this lack of underlying science, there is no transferability between laboratory results and real-world conditions/applications.

Question 2: Accomplishments and progress

This project was rated **3.5** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The technical assessment of understanding the effects of hydrogen exposure and system use on polymer fillers and plasticizers, and permeation and diffusion of hydrogen in exposed materials, follows best practices used in assessing materials used in other fuel systems. Developing this work for the hydrogen domain is very relevant in mitigating cascading risks through more informed design. Sharing information with the community through the Hydrogen Tools portal (H2Tools) is an accomplishment, as is the ongoing standards work.
- The accomplishments and progress toward project goals have been significant, and they appear to be yielding more consistent results with the transition from purchased commercial materials to controlled material compounds for research. Although much of the data matched previous work, it was interesting to see the new findings that were focused on controlled materials and conditions related to hydrogen storage. The project's collaborations (with Sandia National Laboratories [SNL], Ford Motor Company [Ford], H2Tools, CSA Group, etc.) show leadership in the area.
- The development and verification of the test methodologies are the major accomplishments of this project. It is important to have the database, but the existence of the catalog of test methods has tremendous value for other organizations to test other materials and increase the database—so there is much opportunity to leverage this work.
- The project team has exceeded expectations for accomplishments, both in the research efforts and the communication of results for significant impact. This suggests the science of this project and its alignment with industry needs are both strong.
- The data presented were interesting but, in retrospect, not surprising. Elastomers without fillers released the absorbed hydrogen relatively quickly. Elastomers with fillers released the absorbed hydrogen relatively slowly and retained several percent of the initial absorbed amount. Fillers increased durometer readings, etc.
- The project team has developed much new data about basic material behavior in hydrogen environments. For scientific work, the main performance indicator is publication; however, there have been no publications and only three presentations about this work this year.
- If a metric of success for the project is to have a large number of results, then the project does have a series of accomplishments to present. However, one wonders about the value of these accomplishments because of the lack of underlying scientific understanding. For instance, the results reported on slides 9 and 17 are not supported by explanations. As a consequence, if tribology features are sought for another reinforced polymer for which there has not been any testing, these data will need to be taken, and it is not certain whether the developed protocol of the project will apply. Also, there is no explanation whatsoever of the coefficients of friction values reported on slide 13.

Question 3: Collaboration and coordination

This project was rated **3.6** for its collaboration and coordination with other institutions.

- The collaboration is rich and productive. Project partners bring relevant contributions both within the project and through connections in the outside technical community to promote practical impacts. Connections with H2Tools and standards development reinforce these types of tangible extensions of the scientific findings into revised practice.
- The project includes collaboration with a wide and varied population of standards organizations, industry, and research laboratories around the world.

- The project has a good selection of partners. Perhaps Parker and NASA may be helpful; space flight has a good deal of low-temperature exposure.
- This project has very good collaboration and coordination.
- This project would easily achieve a score of outstanding if it were an applied research effort. It is an outstanding example of effective collaboration and coordination between national laboratories, and the Ford partnership adds strength. There is evidence of engagement with other industry stakeholders at an appropriate level for a scientific project. However, there is a critical shortcoming which motivates a lower score: there is no evidence of engagement with the scientific community, universities, or non-national laboratory researchers. These are the most important stakeholders in basic materials research.
- The presentation listed Ford, Pacific Northwest National Laboratory (PNNL), SNL, and Oak Ridge National Laboratory (ORNL) as collaborators. The project team did not clarify whether the group of industry stakeholders who were canvassed to identify issues was larger than the listed names. If so, that would strengthen the work, so it would be good if the presentation could list the stakeholders and the level of response to the canvassing.
- There is a large number of collaborations within this project, but no collaboration results were listed with Dr. Shin Nishimura of Kyushu University. This question was raised at the last DOE Hydrogen and Fuel Cells Program (the Program) Annual Merit Review, but no action has been taken despite the fact that a year has passed. No collaborative results could be found with Dr. Nishimura. This is unfortunate because Dr. Nishimura could have contributed to mitigating the weakness of the project, which is a lack of underlying scientific understanding of the tests.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project is relevant to achieving a sustainable hydrogen and fuel cells industry. Having research that helps with understanding how to quantify compatible materials will ensure the long-term viability of materials used with hydrogen.
- The practical relevance of the work for advancing hydrogen technology through more robust systems is clearly aligned with the Program.
- This research will have an immediate and lasting impact on a global scale on hydrogen energy applications.
- This project is dead on target. It addresses stationary and vehicular concerns.
- The data obtained by the project team are of value to the Program.
- This is a very relevant project, and it has a good deal of impact, for example, on the safe application of materials. The statement was made that testing was shifting from commercially available materials to “specific controlled material compounds.” These compounds were described, but it was not clear why these specific materials were chosen or why the focus changed from commercial materials (which might now be likely chosen for commercial applications as the technology accelerates).
- This project provides critical scientific information about hydrogen materials. The connection of the materials data (rather than test methods) to Barrier A or G needs to be articulated. The project does not address Barrier J in any meaningful way.

Question 5: Proposed future work

This project was rated **3.1** for its proposed future work.

- The investigators appear to have a solid plan to continue the test development and testing. Continued refinement of the test protocols is a very important piece of the work, and to that extent, testing relies on some custom test rigs (such as the pressure cycling manifold setup). It is suggested that the project team consider how to make those facilities/rigs accessible to industry and materials suppliers to test materials and components.
- The project’s future work for fiscal year (FY) 2018 seems well planned and appropriate to meet the stated objectives to address the stated barriers.

- The completion of the standards work is relevant, although the need for that to be funded in this project merits consideration, as the private sector typically has mechanisms to address that separately with minimal cost. Similarly, the generation of data for particular materials is a topic that is generally best addressed by the private sector, once the methods have been developed and the context for use provided by standards. Future work envisioned to further characterize degradation mechanisms, such as effects of pressure and thermal cycling and long-term degradation profiles, is relevant.
- Polytetrafluoroethylene (PTFE) should be lower on the proposed future work list. As a gasket, it will need to be “trapped.” It cold creeps at room temperature, and this creep effect accelerates with temperature. The UTC experience is that an ASME B16.21 (flat ring) style gasket can be an issue in many applications for this material. An ASME B16.20 (spiral wound) gasket that traps the PTFE is often acceptable.
- The future work on slide 31 describes many possible directions for FY 2019–FY 2022. The directions are broad and vague (“build up material properties database”). The presentation does not articulate priorities or a plan for making progress. This demonstrates additional lack of clarity about the objectives and the goal of the work. The project should define next steps more clearly.
- The proposed future work is good, but given the prior progress of the project, it is not clear how the project will come up with a polymeric material damage model. The project has not focused on identifying failure modes and, hence, has not focused future testing on the understanding and modeling of the specific failures pertaining to specific microstructures.
- The proposed future work is a bit broad and undirected. It appears to be more of a plan to maintain a database. Perhaps the team could focus on closing the task and developing a new project or determining an “exit strategy” for the maintenance of the database and information.

Project strengths:

- The project team has strong technical knowledge. The broad range of testing capabilities, as well as the domestic and international partnerships, is a strength. The partnership/involvement with the CSA CHMC 2 standard is strong; combined with populating the H2Tools webpage, the partnerships should produce resources that are helpful to the industry.
- The project is very well structured in terms of the series of steps aimed to “Identify issues” and “Populate [the] database,” and it provides an excellent mechanism for developing and prioritizing tests and test methods and disseminating results.
- There is outstanding collaboration between national laboratories. This project should be the model for national laboratory collaborations. Another strength of this work is its use of each laboratory’s unique experimental capabilities for multidimensional materials characterization.
- The project’s strengths include very effective collaboration and the advancement of relevant scientific protocols based on sound materials science to improve hydrogen system safety.
- This project’s strength lies in the development of research methods and a database of materials performance that are critical to hydrogen energy.
- The strengths of this project include testing capabilities at PNNL, ORNL, and SNL.
- The expertise of the team is this project’s strength.

Project weaknesses:

- The presentation does not really clarify how the candidate materials were chosen (perhaps this came from the stakeholder canvassing). It would be good for the team to clearly state that process, since the database will presumably be used by industry in selecting durable, safe materials for various applications.
- The work on publishing the standard is promising, but it is not yet complete; this will be a milestone for moving from best practices to repeatable approaches. The need for DOE project funding to accomplish future work in standards and materials data generation should be reviewed.
- The project team needs to involve some fundamental science components to help explain the data obtained and their relevant magnitudes. In fact, testing protocols can be established only when the very nature of data and their magnitudes is understood.
- There is a lack of clarity in the objectives and approach, as well as a lack of appropriate collaborations with scientific stakeholders beyond the national laboratories. There is no plan for the preservation and dissemination of scientific data.

- It is recommended that the project team rethink how the data is made available to the engineering community.
- The project lacks a long-term strategy for database maintenance and improvement.
- The project cannot evaluate every material.

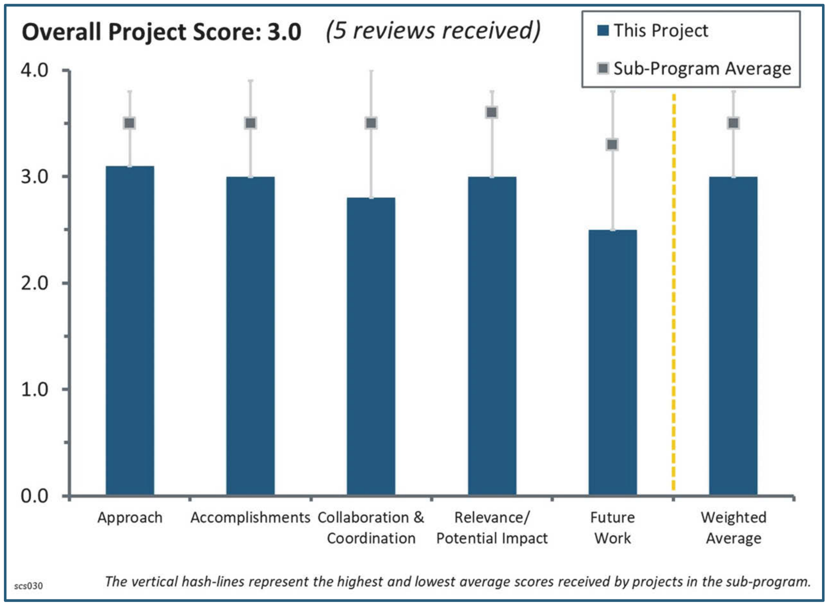
Recommendations for additions/deletions to project scope:

- Polymeric materials for hydrogen infrastructure have been the focus and goal of a number of projects in the Program since 2005. In assessing the progress made so far, it seems that the understanding of the behavior of these materials in the presence of hydrogen has not advanced significantly. More data have been obtained, but a lack of understanding precludes the rational development of codes and standards.
- It would be good to see the intent of the custom material formulations clarified. Also, the team should consider the behavior of key materials in geometries that are likely to be found in typical applications and in applications where there might be hydrogen on one side and air on the other.
- Standards work and the generation of data on particular materials should be deleted from the project scope, as these steps should be fulfilled within the private sector.
- There should be scientific engagement beyond the national laboratories. The project should also publish the results in scientific papers and develop a plan for disseminating raw data to the scientific community.
- The project team should continue to maintain dialogue with the stakeholders.
- More data, at a faster rate, is necessary.

Project #SCS-030: Advancing Fuel Cell Electric Vehicles in San Francisco and Beyond

Jessie Denver; City and County of San Francisco

Brief Summary of Project:



One barrier to increased use of fuel cell electric vehicles (FCEVs) is the complexity of permitting and inspection processes among multiple jurisdictions. This project aims to address this challenge by updating and harmonizing best practices in permitting and inspecting hydrogen fueling stations among the San Francisco Bay Area authorities having jurisdiction (AHJs). Additional project activities include (1) delivering hydrogen safety and best practice education planning, building inspection, and public safety officials and to elected officials in the area; (2) increasing community awareness of the availability and value of hydrogen and FCEVs; and (3) driving market demand for FCEVs through an established group procurement program.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- This is basically an educational outreach project for the public, AHJs, and others, focused on the San Francisco Bay Area. The project engaged in several "events" (e.g., Earth Day, National Drive Electric Week, Electric Vehicle [EV] Week). Of particular interest is the partnering with SunShares, a proven group with established outreach experience and a stakeholder community. This project was able to use EV activities to keep FCEVs in front of stakeholders who were otherwise ignorant of FCEVs and were probably focused only on battery electric vehicles (BEVs). The principal investigator (PI) also collaborated with Tim Lipman (University of California, Berkeley) and Nick Barilo (Hydrogen Safety Panel) to present a tag team presentation at the Fifth Annual Bay Area AltCar Expo and the Green Transportation Summit and Expo, respectively. The PI provided an introductory presentation (titled Hydrogen 101) to prime the audience at those events for Mr. Lipman and Mr. Barilo. This proved to be a particularly powerful and successful approach.
- The approach is sound. It is good to have the team both document and facilitate best practices and do community outreach, education, and training.
- The approach is in agreement with the project objectives.
- The approach should capture "lessons learned" from the interaction with AHJ officials to identify information gaps that could be addressed in areas that are common to all jurisdictions. Also, it is recommended that the team put together a central website dedicated to this project that provides a resource to easily capture and disseminate information (such as webinars, webinar slides, presentation slide decks, etc.). Currently, the project is leveraging other websites, such as the Clean Cities website, that are not as obvious and/or easy to navigate to and find information specific to this project.
- This project focuses on community awareness and outreach in the San Francisco Bay Area only, with no real mechanism to share the lessons learned with other regions.

Question 2: Accomplishments and progress

This project was rated **3.0** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- This project has a very aggressive outreach engagement, and the team partnered with SunShares. Together, they produced a monthly education and training newsletter (with 350 subscribers), maintained a website, worked with the San Francisco Clean Cities coalition, presented webinars for code officials, and gave briefings on FCEV and hydrogen fueling station (HFS) development. The project has a very impressive and expansive list of outreach activities.
- The work with AHJs seems to have been successful; strategically, this is an important group to target because they are very important to the establishment of infrastructure. It is much more difficult to target the general public because it is a large group, and it is difficult to find an effective way of addressing the largest possible group with limited communications and financial resources. A good website would be a good start, but there also needs to be a means of attracting people to the website. There should be a requirement to count the number of hits to the website to measure effectiveness. From the data presented on the review slides, it appears that the number of members of the general public contacted is small. One could argue that that is the job of the auto industry, but the general public still needs independent third-party information.
- The project makes good progress toward its own goals; however, the focused area of the project limits its impact on the DOE objectives. This could be improved through integrating aspects of this project with other funded activities so that lessons learned in other regions could be applied here, and lessons learned here could be better applied in other regions.
- Several activities have been reported for the different points mentioned in the approach. The team conducted many meetings, webinars, and training sessions and met with various people. Nevertheless, quantified data, feedback, and impact are missing. Thus, it would be interesting to provide the number of meetings and people met (industry, regulators, funders, public, etc.), as well as feedback pertaining to any difficulties or questions raised by the attendees. The impact of this project regarding hydrogen perception (positive and negative) after these actions would also be interesting to note. Links to the different meeting materials should be provided for the reviewers. The Hydrogen Station Permitting Guidebook mentioned was published in November 2015. Following these meetings (and as the technology is evolving quickly), perhaps it would be worthwhile or necessary to update the document. It would be good to know how many orders were received after SunShares 2017.
- The community outreach accomplishments are reasonable. The team could have done a bit more in this area. The connection to the SunShares Group Procurement Program is strange—it is not clear why this is part of the project.

Question 3: Collaboration and coordination

This project was rated **2.8** for its collaboration and coordination with other institutions.

- This project has an excellent list of collaborators and coordination activities. This activity is similar to the activities of others, such as the California Fuel Cell Partnership, which is a collaborator on this project. However, the obvious missing partner is H_2USA. Because of this, a score of 4.0 could not be given, particularly since this was noted in the reviewers' comments for the last review. However, it is important to specifically highlight the partnership with Tim Lipman and Nick Barilo and the tag team presentations that resulted from this cooperation—these were really nice.
- The collaborations noted in the project presentation were excellent. There remain key collaborators missing who could help maximize the usefulness of this project. It would have been good to see collaborations with entities that could help ensure project learnings can be used in future projects. It seems as though reviewer comments from the previous year were not adequately addressed. The broader national and international collaborations suggested last year could have helped ensure a more coordinated approach between this project and similar activities that have already taken place elsewhere, or will take place in the future.
- It was good to see collaboration with Tim Lipman—however, it is uncertain how significant that interaction and collaboration was.

- The collaboration level regarding Californian entities was very good. Increased collaboration, or at least a reference to national and international bodies, would be appreciated.
- The level of "outreach" potential is not clear, nor is the size of the respective networks that the collaborating organizations have and the methodology for achieving an ongoing collaboration project. Webinars and conventions tend to be "one-shot" opportunities, but they are also highly specialized to a small community that, in many cases, are already "converts." The larger challenge is to reach outside of the "true believers" group to the general public at large, and it is not clear this project has done that. The lack of the project's own dedicated website is a major problem in achieving this objective. Having a monthly newsletter is a good attempt, but the number of subscribers is still very low (possibly less than 400); perhaps this is because it is buried within the Clean Cities website.

Question 4: Relevance/potential impact

This project was rated **3.0** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- As FCEVs and HFSs are increasingly deployed, the role of and necessity for public outreach and education becomes increasingly obvious. While the vehicles are being deployed at rates that exceed expectations, there are still huge elements of society that simply do not have a clue what this is about, what hydrogen is, or what an FCEV is. For example, according to a story once relayed to this reviewer, a man went to a Toyota dealership in Los Angeles and requested the most environmentally sensitive vehicle on the lot. He was sold a Mirai, which was good. However, when filling up at an HFS, the man expressed that he thought hydrogen was simply an additive for gasoline to decrease emissions. Clearly, there is a lot of educating to do.
- The effort coordinating the AHJs is strategic and appears to have been effective. The team needs to compile a "lessons learned" list so that others can leverage the investment made by the project.
- The project does contribute toward the two DOE goals described in the presentation, albeit in a very limited geographical region. The specific DOE goals are the complexity of permitting and inspection processes among multiple AHJs, and a lack of consumer awareness of hydrogen and FCEVs.
- There is a very significant need to get the word out and to convince the general public and policy makers that fuel cell technology is necessary and complements battery electric drivetrain vehicles well (i.e., they have different features and applications). It is not certain that the team has contributed substantially to informing the San Francisco area of these facts.
- This project may have a very high impact in the acceptance of HFS deployment and, thus, FCEVs in California. This may then also impact other U.S. states and bring instructive inputs for international discussions. However, regarding the information provided for review, there was only a presentation of the numerous actions undertaken, with no real impact assessment.

Question 5: Proposed future work

This project was rated **2.5** for its proposed future work.

- It is good that the team is planning to continue this project for a third year past the planned two-year completion date, with a focus on consumer outreach. The team should look at the potential of coordinating with the automotive industry. Also, it is necessary to build up the mailing list. Those from the Governor's Office of Business Development probably have a large mailing list that could be leveraged.
- The DOE portion of this project is finishing this year. However, the PI will be continuing the effort.
- This project is wrapping up. The presentation notes that the PI will support a third year of the Bay Area SunShares project with outreach to FCEV manufacturers and participation in community workshops. Reporting and dissemination activities appear to be merely turning in a final report to DOE. There is nothing in the presentation that suggests that results will be available in any other form or disseminated more widely.
- The future work and, in particular, the reporting should focus on the lessons learned during this project from all the meetings, webinars, and training sessions that took place. Positive and negative

feedback should be provided to the community, with a list of recommendations to solve the remaining issues both locally in California and also more broadly.
- The project has a very short and weak description of future work planned (even though it is self-funded).

Project strengths:

- This project organized and participated in many conferences, meetings, and webinars aimed at policy makers, safety authorities, trainers, and the general public. These actions are very important in order to facilitate the installation of hydrogen stations and to increase the knowledge and social acceptance of hydrogen technologies.
- There was a significant number of stations planned in the Bay Area. This project helped facilitate community awareness and outreach to permitting officials that could facilitate adoption and more timely approvals for these deployments.
- The project focused on the strategic imperative, which was to work with AHJs to progress permitting. The newsletter is useful and is worth maintaining going forward.
- The idea is good. Outreach to promote fuel cell vehicles as a necessary zero-emissions vehicle option is important.
- This is/was a very aggressive, well-focused, and successful public and permitting outreach activity.

Project weaknesses:

- The degree to which the project accomplished the required outreach to change the perceptions of San Francisco's general public and policy makers regarding fuel cell vehicles is unclear—it does not appear that the outreach was significantly successful. The poster presentation itself was very poor and consisted of printed sheets with thumbtacks. The reviewer visited the poster three separate times and never found the PI present to discuss the project.
- The project lacks its own dedicated website and needs to compile a list of "lessons learned." Furthermore, there was no access to presentation materials, and data on the outreach level achieved (i.e., the number of people attending each event) was lacking.
- The main project weakness is the lack of quantified metrics of all the work performed during these two years, as is the lack of an impact assessment with a list of concrete recommendations for follow-up.
- It would have been good to see collaboration with H_2USA and/or the Fuel Cell & Hydrogen Energy Association (FCHEA) to leverage their more national activities and to feed back to H_2USA and FCHEA this activity's learnings and experiences.
- The project was narrowly focused on a particular geographic region. It was a disappointment to see the lack of robust plans or collaborations to facilitate the sharing of lessons learned.

Recommendations for additions/deletions to project scope:

- The DOE-funded part of this activity is finishing up in fiscal year 2018, so recommendations are not applicable.
- This project is ending. The project learnings should be published and made available for others engaged in future efforts in other regions.
- The main recommendation would be for the project team to perform a real impact assessment, leading to a list of concrete recommendations of actions to further facilitate HFS deployment.
- Given the small budget and limited resources, the focus should be on working with AHJs, political officials, and developers, not on public outreach.
- The project team should do more significant outreach to change public perception.

2018 – Systems Analysis
Summary of Annual Merit Review of the Systems Analysis Sub-Program

Summary of Systems Analysis Sub-Program and Reviewer Comments:

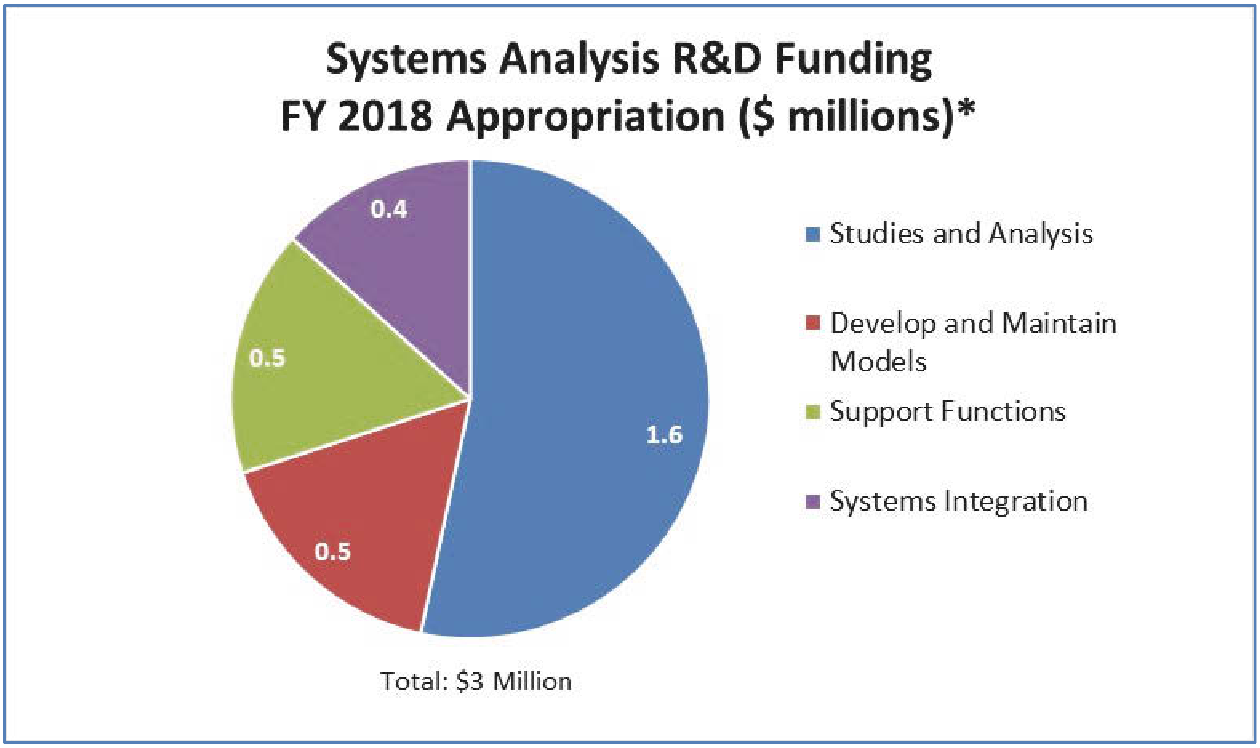
The Systems Analysis sub-program supports the decision-making of the Fuel Cell Technologies Office by providing a greater understanding of technology gaps, options, and risks for early-stage research and development (R&D). The sub-program's goal is to provide systems-level analysis to support hydrogen and fuel cell technology development and technology readiness by evaluating technologies and pathways, including resource requirements. The sub-program's analytical efforts focus on technoeconomic analysis of fuel production-to-utilization on a lifecycle basis for light-, medium-, and heavy-duty fuel cell electric vehicles (FCEVs) and the H2@Scale concept. The sub-program also conducts analysis to assess cross-cutting issues such as the integration of hydrogen and fuel cells with the electric grid for energy storage. The Systems Analysis sub-program aims to enable hydrogen technologies that support infrastructure development through innovative R&D. The results of Systems Analysis efforts help guide the selection of R&D projects and estimate the potential value of specific R&D efforts. The sub-program collaborates with industry and other federal offices and agencies (e.g., the DOE Offices of Fossil Energy and Nuclear Energy, U.S. Department of Defense, and U.S. Department of Transportation) to leverage outside activities, coordinate efforts, and build opportunities for new technology applications and input.

The Hydrogen and Fuel Cells Program (the Program) reviewers commended the Program's focus on H2@Scale and the prioritization of hydrogen production and infrastructure R&D. They identified the H2@Scale market assessment as a keystone analysis for the Program and recommended that it incorporate broader sensitivity analysis to increase credibility of the evaluations. The reviewers also considered the Systems Analysis work on hydrogen supply and demand interaction critical to H2@Scale, as well as the efforts to characterize hydrogen production across the United States. The comparative evaluation of FCEVs and plug-in electric vehicles on various vehicle platforms was also highlighted as a sub-program accomplishment.

The reviewers praised the Systems Analysis robust modeling toolkit but offered a cautionary suggestion to screen proposed analysis projects to avoid redundancy. It was recommended that the modeling project template incorporate industry/stakeholder review as a standard element to add value to the projects. Reviewers suggested that the sub-program evaluate the energy and environmental impacts of hydrogen liquefaction on a lifecycle basis to substantiate the benefits of the technology. Reviewers also suggested the sub-program initiate analytical projects aimed at better understanding the market and technology transition phase (versus the market launch phase) within the next 5–10 years.

Systems Analysis Funding:

The fiscal year (FY) 2018 appropriation for the Systems Analysis sub-program was $3 million, allocated as indicated in the figure below. Funding continues to focus on conducting analysis using models developed by the sub-program. In particular, analysis projects are concentrated on the hydrogen value proposition for H2@Scale, the levelized cost of hydrogen from renewable hydrogen production pathways, the impacts of hydrogen delivery/onboard storage/fuel cells on early-stage R&D needs for onboard hydrogen storage options and associated costs, emissions from hydrogen pathways for fuel cell medium- and heavy-duty trucks, and hydrogen fueling station business assessments.

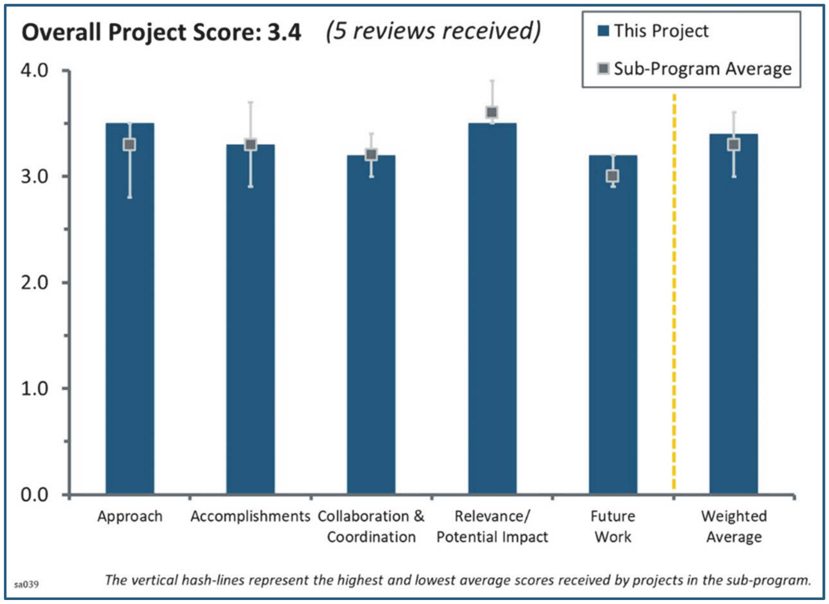

Systems Analysis R&D Funding
FY 2018 Appropriation ($ millions)*
0.4
0.5
0.5
1.6
Studies and Analysis
Develop and Maintain Models
Support Functions
Systems Integration
Total: $3 Million

Project #SA-039: Regional Water Stress Analysis with Hydrogen Production at Scale

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:

Argonne National Laboratory (ANL) has expanded the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET™) model to include water consumption. ANL has (1) identified major contributors in the upstream supply chain to water consumption and (2) evaluated water consumption for the fuel production stage.



The vertical hash-lines represent the highest and lowest average scores received by projects in the sub-program.

Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- Data sources are appropriate, and the use of existing models to leverage existing pathways is a good use of laboratory resources. The impact analysis approach is appropriate; mapping water resources for freshwater and non-freshwater, as well as water consumption and scarcity, is useful in assessing how different forms of energy production affect water quantity/availability across regions.
- The approach ties together a complex set of variables including regional environmental aspects, power sources, and consumption. It would be good to also include access to water sources that are not freshwater.
- It is nice to see some focus on water consumption using a consistent analysis approach. It is necessary to ensure water consumption is taken into account, similar to CO_2. The Available WAter REmaining (AWARE)- and GREET-type analysis is a good approach.
- Overall, this is a valid and worthwhile evaluation. It is suggested that the project more clearly compare water requirements, including those for agriculture.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- Understanding groundwater recharge and human impact by region is not an easy task. ANL did a good job mapping this information. Also, understanding the impact of different electricity generation technologies located in either water-stressed or water-abundant areas provides a robust means to quantitatively evaluate the impact of thermoelectric and renewable electricity production. It is a plus that the team is integrating this project with H2@Scale to pair resource availability and demand with water availability.
- Given the basis of the study, an excellent job was performed. It is necessary only to consider overall water usage to put the results in perspective.
- The results of this study are very helpful for informing both national policy and production planning.
- This project contains a nice aggregation of water data from various sources.
- DOE has recently presented other analyses that seem to contradict the conclusion that water demand for fuel cell electric vehicles fueled by hydrogen from electrolysis is hugely higher than any other scenario analyzed. These cases should be reconciled.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- A specific description of the roles of other collaborators was provided. There was good coordination with Pacific Northwest National Laboratory (PNNL) to incorporate higher resolution for regional water consumption. It would be valuable to have utility perspective on the team.
- With the variety of water data presented, it is evident that collaboration was necessary to aggregate and summarize.
- The list of partners and collaborators is appropriate, as it includes the U.S. Environmental Protection Agency, other national laboratories, the Army Corps of Engineers, and even academia.
- The collaboration was well done.
- It seems that the results of this study have not been thoroughly reviewed. There is evidence of this in the presentation. The presentation is mainly focused on the communication of data and results, and it lacks analysis and potential impacts. What this means for the production industry decision maker, or for the local or federal policy maker, is unanswered. The summary slide provides some of this information, but the bulk of the information is rather difficult to interpret. A review by project collaborators would ensure that the communication of information would provide a better interpretation and meaning for each level of information.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- It is necessary to be sure all sustainability aspects are taken into account when evaluating technologies and alternative energies. This project brings in a critical resource analysis to ensure a sustainable future for all communities and regions is created.
- As the population grows and the climate changes, water quality and quantity issues have been exacerbated across the country. Understanding the impact on water from our energy sources will provide a map for future developments in grid infrastructure.
- An analysis of the full impact of energy technologies is highly important to understanding potential risks in implementation. Water is a key resource that needs to be understood as part of the analysis.
- This is a study that needed to be done, but the answer is perhaps relatively obvious: the overall impact on water is not great.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- The proposed future work is important in grounding the analysis. Understanding where the water is actually consumed in processes that are upstream from the hydrogen production could change some of the scarcity footprints.
- The proposed future work is appropriate.
- The proposed future should include possible water intensity reduction potential by looking at alternative water-handling and reuse options such as closed-loop water and reclamation systems.
- It is necessary to add water requirements for agriculture, in particular, to show how small the hydrogen generation effect is.

Project strengths:

- This project is highly relevant in the overall analysis of energy and water. The project represents high-fidelity modeling and interactions that are feasible only at a national laboratory.

- The methods used (i.e., AWARE and GREET) bring a consistent approach to analyzing water intensity data regionally and by production technology.
- This is a knowledgeable team, able to leverage the GREET model. The strong partnerships provide data and feedback, and the topic is relevant.
- The analysis is excellent; it is necessary only to put the results into an overall water-usage perspective.
- This project has relevance and adds improvements to the main life-cycle analysis.

Project weaknesses:

- While significant progress has been made, an analysis of this scale has to be done in phases. Completing the next layers of detail will be important to providing a balanced picture. Also, some of the output seems contradictory to other analyses within DOE.
- The project presenter had a hard time explaining the carbon fiber factor or stress factor. Perhaps it could be made clearer.
- Some stakeholders may not understand the importance of water in overall sustainability.
- It is necessary to compare usage for hydrogen generation to overall water usage.
- The project needs better communication of analysis and impact.

Recommendations for additions/deletions to project scope:

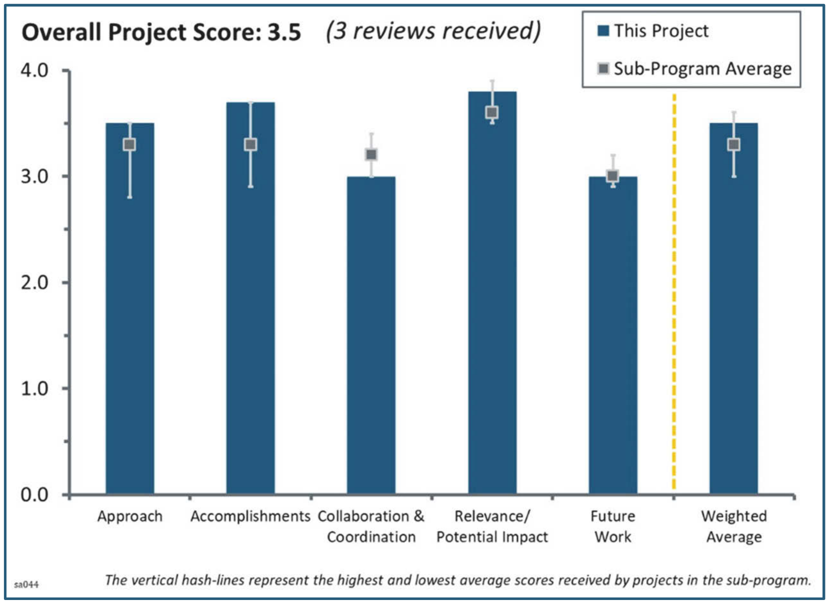
- The scope of the project is appropriate; future modeling work is well defined and contributes to the overall advancement of the body of knowledge.
- This is a recommendation on developing a regional water impact, based on the deployment of electric vehicles in a region. For example, as the California zero-emissions-vehicle mandate displaces gasoline and reduces oil refining, it would be good to know what the net impact of the water situation there will be in 2050. Also, a reduction factor for incorporating closed-loop or reclaim systems into the production processes for electrolysis could be useful.
- It is recommended that the project add an overall water usage perspective.

Project #SA-044: Cost–Benefit Analysis of Technology Improvement in Light-Duty Fuel Cell Vehicles

Aymeric Rousseau; Argonne National Laboratory

Brief Summary of Project:

This project aims to quantify the impact of fuel cell system improvements on energy consumption and economic viability of fuel cell electric vehicles (FCEVs). The project will (1) analyze fuel cell stack, hydrogen storage, and fuel cell system improvements in terms of their impacts on the cost of driving FCEVs and (2) evaluate whether current fuel cell and storage technology targets are sufficient to make FCEVs viable.



Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- Autonomie is a very robust and comprehensive model. Leveraging this tool to assess the impact of technological changes helps justify Fuel Cell Technologies Office (FCTO) programs. The vehicle technologies compared in the project are appropriate. The methodology to cost U.S. Department of Energy technical targets and the associated benefits is a smart way to figure out what the tipping point is where better technology does not translate into better economics.
- The project is using validated models in its analysis. The team provided a range for each analysis. It was unclear whether the team validated some of their assumptions and results concerning battery electric vehicles and plug-in hybrid electric vehicles (PHEVs) with the Vehicle Technologies Office.
- The project approach is reasonable and effective for evaluating target impacts on vehicles. It would be helpful to show more explicitly how Autonomie was used, the drive cycles, and other assumptions.

Question 2: Accomplishments and progress

This project was rated **3.7** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The project is almost complete and is providing valuable information to guide DOE's future research and development (R&D) plans. The fuel cell peak efficiency versus dollars-per-kilowatt savings curve is an excellent representation of how more efficient fuel cells may not be worth the extra cost.
- The project's analysis was able to predict the impact not only of achieving the DOE targets but also of achieving close to the targets. The analysis does a fair job comparing the fuel cell vehicles with conventional vehicles, hybrid electric vehicles, and PHEVs. The analysis on hydrogen cost and benefits of higher system efficiency was very interesting. The team should vet the analysis and results with industry and with the Vehicle Technologies Office.
- Analysis results were generated in this project. Recommendations would have been expected in terms of which targets are more impactful. Even though this project is a benefits analysis, some relationship to technology progression rate or cost of improving technology could be applied to estimate which targets are lower-hanging fruit in the cost–benefit context.

Question 3: Collaboration and coordination

This project was rated **3.0** for its collaboration and coordination with other institutions.

- U.S. DRIVE Partnership technology teams have worked with the project to validate the assumptions. It would be good to know whether results agree with original equipment manufacturers' (OEMs') views of future technology.
- More collaboration would have been expected, for example, with automotive OEMs (e.g., Honda, Toyota, General Motors).
- There was limited collaboration in this project. It is recommended that the project invite industry (OEMs) to an in-depth review of the approach and results.

Question 4: Relevance/potential impact

This project was rated **3.8** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- This type of analysis is essential to determining the impact of target-setting. It would be helpful to determine whether targets among other vehicle technologies are comparably aggressive. When subsequent analyses use targets, the program with most aggressive targets will appear to be "winning" the technological race. Thus, it is essential to have achievable and comparable target-setting among all vehicle drivetrains (e.g., electric vehicles).
- This project is important because it provides justification for the goals established by DOE. It answers the following questions: (1) what the benefits are of meeting the targets, (2) what the impact is of various components on weight, cost, and energy consumption up to the FCTO targets, and (3) what the point of diminishing returns is.
- This analysis helps inform the direction of FCTO.

Question 5: Proposed future work

This project was rated **3.0** for its proposed future work.

- It would be helpful to do some validation testing on the model. As FCEVs are becoming available and the various OEMs have different energy storage density, stack efficiency, etc., it would be essential to validate the model.
- The project will not continue beyond August 2018.
- This is the final year of the project.

Project strengths:

- This project shows an in-depth knowledge of Autonomie. This is a strong team, knowledgeable and technically skilled. This project is of high importance.
- The team is using good models for their analysis. The approach is well-thought-out.
- The analysis leverages rigorous vehicle modeling models.

Project weaknesses:

- The principal investigator's presentation results seem biased by favoring FCEVs. For instance, slide 12 mentions at the top that FCEVs could reach life-cycle cost parity with PHEVs by 2025, but this is the most unlikely of cases. Furthermore, this would happen only when DOE's R&D targets are reached. In the other two cases, parity is reached either in 2030 or in 2045.
- The team should have industry OEMs review this project. They should look at medium- and heavy-duty applications.
- Validation of real-world vehicles will be necessary.

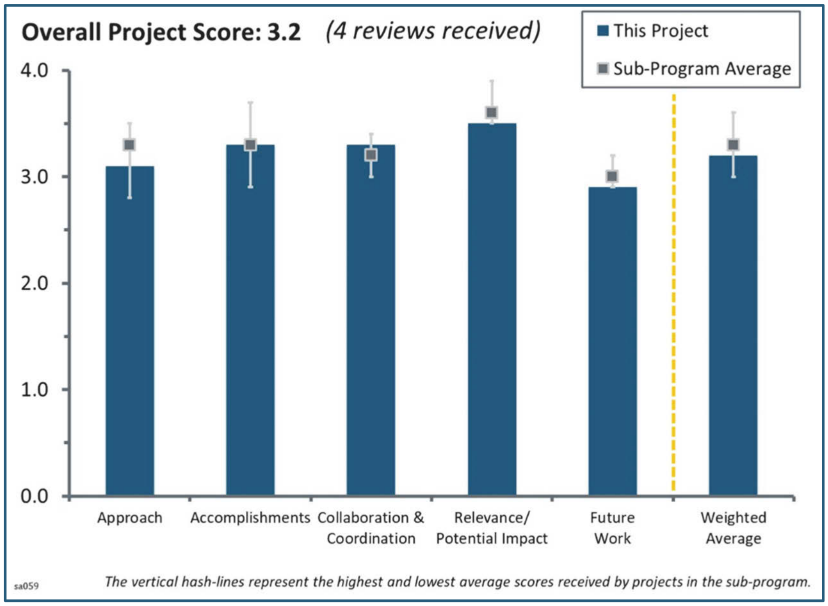
Recommendations for additions/deletions to project scope:

- It would be good to see the results discussed with OEMs to ensure that the results are accurate. It would also be good to see the "targets" referred as the "DOE R&D targets" to avoid confusion. These are ultimate targets that will allow technologies to compete with conventional internal combustion engine vehicles but are not likely to be achieved in the near term; this needs to be clarified. Other than that, the project is excellent.
- The team should include efforts for validation or, more practically, collaborate with vehicle testing-capable entities.
- The team should look at medium- and heavy-duty applications.

Project #SA-059: Sustainability Analysis: Hydrogen Regional Sustainability

Elizabeth Connelly; National Renewable Energy Laboratory

Brief Summary of Project:



This project is conducting a sustainability analysis of hydrogen supply and stationary fuel cell systems using the Hydrogen Regional Sustainability (HyReS) framework. Investigators will develop regional metrics around upstream hydrogen supply chains, ensuring consistency with existing frameworks and tools used by engineering firms, the sustainable business community, and green investors. The project will leverage the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET™) model with the spatial detail of the Scenario Evaluation, Regionalization, and Analysis (SERA) model. Outcomes will include pathway cases, a beta framework, and a final public framework.

Question 1: Approach to performing the work

This project was rated **3.1** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project represents a good application of different models to support results and analyze different scenarios. Incorporating all of these different analyses and tools with sensitivity analysis is a highly complex task.
- The objectives and barriers were identified, and the project supports the sustainable development of alternative fuel and vehicle technologies.
- The basis for study and the approach integrating models with input from other organizations were both excellent and very worthwhile.
- The HyReS analysis is a good idea. The modeling suite is mostly appropriate. It was not clear whether the project team had the U.S. Department of Energy's Vehicle Technology Office (VTO) and Bioenergy Technologies Office (BETO) validate the assumptions and results in their respective areas. Current hybrid electric vehicles (HEVs) have a much higher range than vehicles with internal combustion engines (ICE), yet the charts presented do not show the improvement—this should be investigated. It is not clear why Future Automotive Systems Technology Simulator (FASTSim) results were chosen over the GREET model data (see slide 11). It is not clear why the project team is not using Autonomie. Autonomie is validated by the industry and is the industry standard. It seems that Autonomie provides more information than FASTSim. FASTSim may have a faster processing speed, but if the information it provides is not as complete and is not validated, then the increased processing speed is not as useful. It is recommended that rather than updating FASTSim, the project team integrate Autonomie. It is good that the project is using BETO and VTO performance goals from the Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- To support DOE's planned direction, it is necessary to complete this type of analysis, with solid data and impact to health and economics, as well as energy sustainability.
- The project has made good progress toward attaining the stated goal.
- The researchers have made solid progress. The researchers should consider having representatives from BETO and VTO review the assumptions and outputs from the models. The researchers should include plug-in hybrid electric vehicles (PHEVs). Note that PHEVs are already included in Autonomie, as are plug-in hybrid fuel cell vehicles. This is another example of why the team should be using Autonomie. Current HEV miles per gallon is considerably higher than that of the ICE vehicles, yet the charts show very similar performance. This is surprising and should be explained.
- Some of the accomplishments produced results that have already been calculated by other teams. For instance, on slide 12, the life-cycle petroleum consumption of different fuel/vehicle alternatives were published in the cradle-to-grave study. Similarly, the results on slide 11 were calculated by the U.S. DRIVE Partnership Integrated Systems Analysis Tech Team two years ago. It is unclear why the calculations had to be redone using a different model instead of just updated.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- Overall, this project has good coordination.
- The partnerships within this project seem adequate.
- The project leads are working with Argonne National Laboratory and have requested input from some external reviewers. It would be interesting to get reviews from General Motors, Toyota, Honda, and other original equipment manufacturers (OEMs) that make HEVs, PHEVs, and fuel cell electric vehicles.
- The collaborators were listed with model names, but there was not much description of how the collaborators interacted with each other or what the roles were.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- There is good effort within this project to make sure that batteries and hydrogen are being compared on a common scale and that analyses are revisited when there are believed to be differences.
- There is a strong focus on integrating various models to develop an overall assessment.
- This information is very interesting and necessary to help with planning. The quality and completeness of the information may be improved by using Autonomie in place of FASTSim.
- The project contributes to a better understanding of the environmental effects of displacing conventional vehicles with hydrogen fuel cell technologies. However, the project would be more impactful if other aspects of sustainability and additional criteria air pollutants were included.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The future work describes less concrete tasks than previous years, and it mainly seems to involve the refinement of existing results. While this is valuable, it would be good to describe how this refinement might improve the model conclusions more explicitly.

- In the reviewer response, the presenter discussed cost versus price—this was a good explanation. In slide 19, the presentation said that calculating price was a remaining challenge. It is recommended that the team call it “minimum selling price,” per the response in slide 16. One of the future work tasks was to “Implement Framework,” but it is not clear what this means. Finally, it is recommended that the project team use Autonomie.
- The project includes only NO_x and $PM_{2.5}$ (particulate matter – fine particle) emissions. Other criteria air pollutants such as sulfur and volatile organic compounds (VOCs) are not discussed. It is understood that these elements have not been included because these are the only pollutants with associated externality costs in the Estimating Air Pollution Social Impact Using Regression (EASIUR) model. Finding another source of externalities is recommended for a more comprehensive assessment. Other aspects of sustainability are not addressed; this analysis is purely environmental, and it does not integrate social or economic aspects.
- The project team will continue work as planned toward completion of the study.

Project strengths:

- This project looks at the societal costs of various vehicle technologies to better understand the implications of the research, development, and deployment plans. The team is very strong and is using a broad, powerful suite of modeling tools.
- This project has a thorough understanding of the available modeling tools and an impressive integration of the inputs and outputs.
- This project has made an excellent effort to integrate various models. This is very important.
- The project team possesses strong technical knowledge and partnerships.

Project weaknesses:

- It would be helpful to more clearly describe the benefits of additional refinement of the models.
- Only the environmental aspect of sustainability was tackled, and that too only partially. Some of these analyses have already been performed by other researchers.
- The project team needs to have more OEMs and perhaps have the VTO review the data and results. The team neglected to include PHEVs, and the HEV assumptions may not be accurate. It is not clear why the team used FASTSim over GREET. It could appear to a critic that this was done to make the fuel cell technology look better. To be clear, it seems acceptable to use FASTSim over GREET, but critics may raise this issue. It is recommended that the project team clearly justify their use of FASTSim.

Recommendations for additions/deletions to project scope:

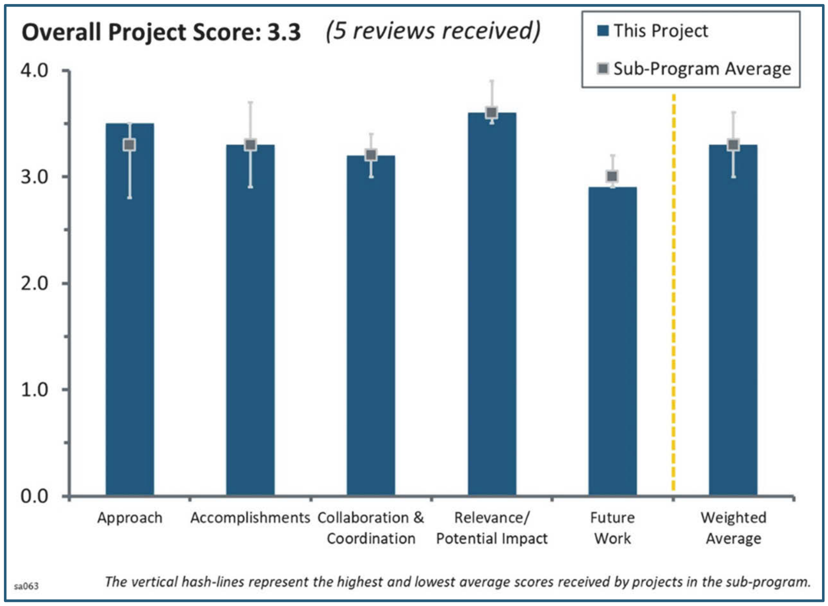
- This project is complete, as intended.
- It may be interesting for the team to do a sensitivity analysis to see how varying key metrics would change the output.
- It is recommended that the project team add other criteria air pollutants such as sulfur and VOCs. Once these results are completed, the team should include carbon dioxide and carbon monoxide from GREET. It is understood that these elements have not been included because these are the only pollutants with associated externality costs in EASIUR. It is recommended that the team find another source of externalities for a more comprehensive assessment. Also, the name of the project should be changed from “sustainability analysis” to “environmental analysis.”

Project #SA-063: Regional Supply of Hydrogen

Michael Penev; National Renewable Energy Laboratory

Brief Summary of Project:

This project aims to estimate existing hydrogen production assets and potential excess production capacity and provide enhanced forecasts for near- and long-term hydrogen supply chains. The analysis forecasts production capacity expansion requirements for the growing fuel cell electric vehicle (FCEV) market demand, simulates regional supply chain network dynamics, and incorporates market competition considerations.



Question 1: Approach to performing the work

This project was rated **3.5** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project provides a thorough evaluation of a very important aspect of providing hydrogen where it is expected to be needed and estimating the cost of the hydrogen at the dispensation point.
- This project is conducting a very impressive and in-depth analysis of future scenarios for hydrogen fueling.
- The approach is realistic for achieving scale. The team should consider doing an optimization on centralized compression with final stage compression at or near the usage points.
- This project is looking to overcome the high cost of hydrogen delivered at the pump. However, the approach is rather simplistic since it assumes that land will be available when and where it is needed to lay down hydrogen pipelines. Right-of-way is a very real problem that would cost time and money. Also, it is not clear how hydrogen sources are estimated to compete economically against each other in the future, but coal and biomass gasification are currently expensive technologies that cannot compete with steam methane reforming (SMR). Furthermore, it is too simplistic to assume that 20% of all SMR is in overcapacity and will be available to the market.
- The dominance of the proposed concept, H2Grid, in the results suggests a bias and a lack of structure in the approach. This approach leads the results, and this presentation seem to endorse the idea of H2Grid.

Question 2: Accomplishments and progress

This project was rated **3.3** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The modeling results are well described and supported. The time-based model shows how the mix of technologies changes as a function of vehicle deployment and infrastructure rollout.
- Given the complexity of the supply chain system, the team has done a good job laying out a framework to analyze and optimize.
- The project is making good progress to meet its objectives.
- This project meets all DOE Hydrogen and Fuel Cells Program goals established for this analysis project.
- This project has mixed results. The analysis tools developed for this work are impressive, but both the subjects selected for analysis and the results are underwhelming.

Question 3: Collaboration and coordination

This project was rated **3.2** for its collaboration and coordination with other institutions.

- There is strong coordination with DOE laboratories, effectively using various models to develop an overall integrated assessment.
- The team includes appropriate representatives from industry, a utility, and other laboratories. The type of feedback was not described in detail.
- The project would benefit from collaboration and feedback with city planners and utilities that can talk about the likelihood of being able to install hydrogen pipelines near major urban centers, as defined in the scenarios. It remains to be seen whether the expansions and costs are realistic.
- This project should consider a more diverse group of collaborators to achieve a better diversity of future outcomes, particularly when assuming the scope of a nationwide assessment predicting results into the next 30 years.
- There could be value in bringing some large gas utilities into the project to validate pipeline assumptions and costs.

Question 4: Relevance/potential impact

This project was rated **3.6** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- Understanding the potential scenarios for infrastructure rollout and distribution mechanisms is necessary to create an overall vision and get industry buy-in.
- This project is entirely relevant, focusing on a very important overall hydrogen distribution/cost assessment.
- This project addresses the fundamental issues in achieving scale.
- The relevance of this project is directly related to its accomplishments.
- The Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan states that "there is a high investment risk for developing a hydrogen delivery infrastructure, given the current absence of demand for hydrogen from the transportation sector." This is still true today—the demand is too low to make these investments economically feasible. Given that the project forecasts that infrastructure development will commence in 2021 (only three years away), it is unlikely that the demand for hydrogen for transportation will be sufficient to justify the investment. However, it is promising as a delivery solution because it would considerably lower the cost for the station owner.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- The proposed future work considers the relevant factors affecting hydrogen generation/distribution and associated costs and challenges.
- It is a positive measure that electrolysis will be included in the hydrogen production options. Future work should also include potential cost, using all the hydrogen production sources listed in the presentation. It would also be important to calculate the cost of the hydrogen station under the semi-central delivery pathway.
- The team might consider other scenarios and the impact on hydrogen costs in various markets.
    - It is unclear what effect large FCEV deployments in a region would have on existing refinery hydrogen demand and whether this would accelerate depreciation of hydrogen plants. The average hydrogen cost in these markets, using the excess hydrogen in the various distribution channels, is unknown. Perhaps an oil company partner would be able to help with this.
    - Water transportation is excluded from the model. The team might consider the impact of shipping liquid hydrogen (LH2) from major production areas and having LH2 unloading terminals in large ports for use in ports and initial pipeline networks.

- The potential benefits of further refinement on the buildout algorithm are not really specified. Aligning the financial models to be more consistent with industry is very important since it affects Hydrogen Analysis (H2A) model costs, and current default assumptions are probably overstated.
- Unless this project is better scoped and titled as “H2Grid” analysis, future work should consider the potential for outcomes in which H2Grid is prohibited by circumstances cited in previous reviews, such as regulations or insufficient market investment.

Project strengths:

- The project is complex, but the team breaks down the major hydrogen costs and challenges and addresses large-scale hydrogen production with a rational approach. The team has been able to gather realistic data from collaboration with others on pipelines and hydrogen production costs.
- The model clearly represents a level of computing power that is accessible only at a national laboratory level. The evolution of various factors over time is highly informative and relevant.
- The project seeks to reduce the cost of delivered hydrogen and leverages existing modeling tools. The project team has engaged a number of technical experts.
- The excellent integration of models collaboratively with other DOE organizations helps in developing valuable estimates of future hydrogen pathways and their costs.
- This project’s strength lies in its analysis model development.

Project weaknesses:

- There are no weaknesses evident.
- The project makes unrealistic assumptions about the availability of hydrogen supply and assumes that land will be available to lay hydrogen pipelines in and around urban areas. The idea of H2Grid is good, but it is unclear who would pay for the buildout.
- There is an immense amount of hydrogen produced for oil refining; this displaced hydrogen should not be ignored in the cost calculations as mass deployments of FCEV light- and heavy-duty vehicles emerge.
- The bias toward a single-solution future should be more distressful to the researchers; it points to a lack of diversity in collaborators.
- The type of feedback solicited from industry could be better described.

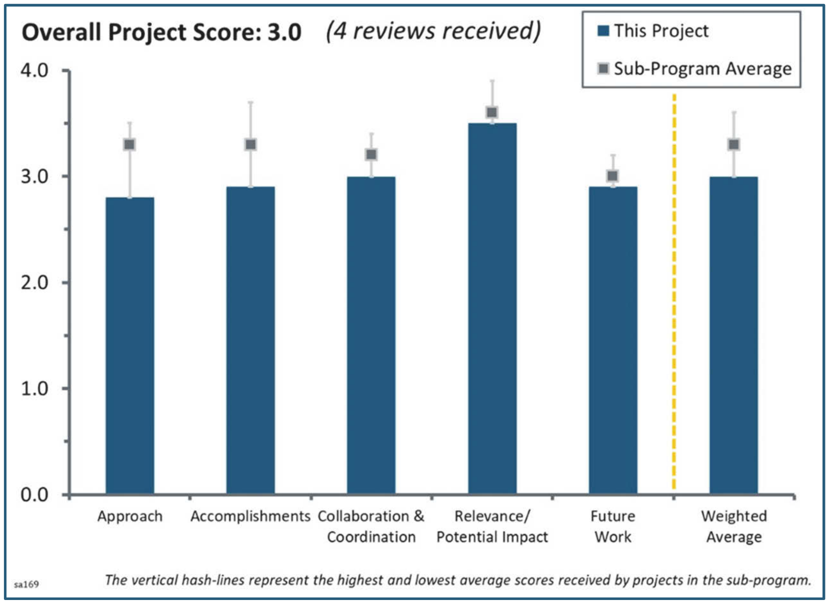
Recommendations for additions/deletions to project scope:

- The project team should increase collaboration with city planners and utilities that can provide feedback about the likelihood of installing hydrogen pipelines near major urban centers. The team should also estimate the cost of hydrogen refueling stations without production, compression, or on-site storage to assess the economic benefits for the station owner, compared to the stations that we have today. It is recommended the team understand the likelihood of having access to hydrogen overcapacity now and in the future, given the forecasted buildout. The team should also define who is expected to pay for future hydrogen pipeline buildout and expand collaborations to include potential investors (i.e., cities, utilities).
- The project scope is excellent as is, but it is suggested that the team check electrolyzer costs in the analysis—this seems higher compared to other available data.
- The team should consider adding water transportation of LH2 from large hydrogen production areas to unloading terminals into high-density FCEV regions.

Project SA-169: Market Segmentation Analysis of Medium- and Heavy-Duty Trucks with a Fuel Cell Emphasis

Chad Hunter; National Renewable Energy Laboratory

Brief Summary of Project:



This project provides stakeholders a broad assessment of medium-duty (MD) and heavy-duty (HD) fuel cell vehicle market opportunities and helps guide future U.S. Department of Energy investments in the area. As part of this effort, systems analysis models that assess cost and market barriers to fuel cell vehicle adoption will be enhanced and expanded. The tools and models used in analysis include Future Automotive Systems Technology Simulator (FASTSim) for vehicle optimization to obtain vehicle cost, fuel economy, and weight; and Scenario Evaluation, Regionalization, and Analysis (SERA) for stock modeling and modeling of direct costs, opportunity costs, and other value streams. The SERA model will be used to calculate total cost of ownership for each vehicle class and vocation by region.

Question 1: Approach to performing the work

This project was rated **2.8** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The use and combination of very robust and well-established models such as FASTSim and SERA are key for successfully achieving the main objectives of this work.
- The project team makes use of the excellent models available at National Renewable Energy Laboratory and other national laboratories in conducting a well-planned study.
- The SERA tool and Hydrogen Analysis (H2A) work are done well. It is unclear why the team is using FASTSim and not Autonomie. Autonomie is the industry standard, and it has already been developed and validated. The extra information, and the fact that it is validated and needs minimal development, makes Autonomie well worth the additional computational time required for its use. The team should have done ranges of performance or a sensitivity analysis. It is unclear why the team did not include plug-in hybrid electric vehicles (PHEVs) in their analysis. This is a significant gap, as PHEVs are gaining popularity even with MD and HD vehicle manufacturers. The data the team used in the SERA stock models needs to be updated.
- This project should be using Autonomie instead of FASTSim to carry out calculations. Autonomie is a more robust model with the ability to simulate the cost and performance of many different types of vehicles (including light-duty [LD], MD, and HD vehicles) and alternative fuels. This model has been around for more than 10 years, and Argonne National Laboratory (ANL) continuously updates the model with industry data. Furthermore, it is important that the project team include today's technology costs, in addition to the 2020 and 2040 targets, to understand the cost gap that needs to be bridged.

Question 2: Accomplishments and progress

This project was rated **2.9** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- As this project recently started, the accomplishments are somewhat limited. However, the current progress being presented (mainly on the FASTSim update and validation for optimizing MD and HD vehicles) shows that the project is on a good track to achieve its main objectives.
- There is excellent progress to date, considering the project started in January 2018. Accomplishments include the validation and enhancement of necessary models, such as SERA and FASTSim.
- The project team has made considerable progress toward the project goals. The initial results can be used to provide guidance to DOE development. However, it is disappointing that a sensitivity analysis was not done. This probably could have been done if the team had used Autonomie. Also, the team is missing PHEV vehicles. These are significant weaknesses in this project.
- The accomplishments are good, given that the project started in January of this year. However, the time that the team is spending updating FASTSim could be better used by running cases and analyzing results in Autonomie. Autonomie already includes MD and HD vehicles, and it is more comprehensive.

Question 3: Collaboration and coordination

This project was rated **3.0** for its collaboration and coordination with other institutions.

- The input and feedback being provided by such strong players in the MD and HD vehicle space, such as Cummins, Inc., and Toyota Motor Corporation, are excellent for this project. The addition of Nikola Motor Company also provides great value from the fuel cell perspective.
- Vanderbilt University's Yuche Chen has good modeling capabilities in this field. The use of the VISION model as a benchmark is good because VISION emulates the U.S. Energy Information Administration's vehicle stock projections.
- The team had several industry partners as peer reviewers. It is recommended that the team review its approach, assumptions, and results with the DOE Vehicle Technologies Office (VTO).
- Additional modeling collaboration with ANL is essential to at least validate the results of this project using Autonomie. The team should involve VTO to provide feedback. The U.S. DRIVE Partnership should also be involved.

Question 4: Relevance/potential impact

This project was rated **3.5** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The MD and HD vehicle market is becoming more and more important in the transportation sector. Fleet refueling may be the initial deployment path for larger-scale hydrogen and fuel cell utilization.
- As the interest in hydrogen and fuel cells keeps growing beyond LD transportation to the MD and HD vehicle market, this analysis is extremely valuable to understand the potential of this transportation sector.
- Since the DOE Fuel Cell Technologies Office (FCTO) is moving in this direction, this analysis will be helpful. The project team could increase the potential impact by including PHEVs and a sensitivity analysis.
- Autonomie already has a series of papers on MD and HD trucks: https://www.autonomie.net/publications/papers_heavy_duty.html. Although none of these papers directly address market segmentation, it is easy to extract that necessary data to conduct market segmentation analysis using Autonomie.

Question 5: Proposed future work

This project was rated **2.9** for its proposed future work.

- Although not on the slides, the presenter said that a large amount of sensitivity analysis will be done with FASTSim, which is an excellent idea. SERA needs data on truck travel over time to site location; the team will work on this. Also, idle versus driving time will be updated, and grade (slope of the road) effect will be added.
- The proposed future work presented was clearly defined and well aligned with the strategy and approach to obtain the main objectives of this project.
- It is good that the project team is planning on performing a sensitivity analysis. The team should continue to get their results validated by original equipment manufacturers, U.S. DRIVE, and VTO. The stock modeling must be updated, and PHEV vehicles are missing from the analysis.
- It is important that the project team not duplicate work. Autonomie could have been used from the beginning to produce faster and more accurate results. Furthermore, today's cost should also be included in the analysis, not just the 2020 and 2040 ultimate research and development (R&D) targets.

Project strengths:

- The project has excellent models and a current set of available data. There is excellent collaboration with appropriate experts. The project's focus is on major market segments relevant to the larger-scale deployment of fuel cells and hydrogen.
- The project team is examining an important new direction for fuel cells and has made solid progress in the project efforts.
- The objectives are clear and relevant.
- This project's strength includes its modeling capabilities.

Project weaknesses:

- There are no weaknesses in this project.
- The team needs to interact more with the California Air Resources Board because the board is doing a good deal of work in this area. Also, the project team needs to think about how the results will be presented. For example, it is unclear whether the results will look like the DOE FCTO low/medium/high results for LD vehicles in terms of cost per mile, based on ANL's Autonomie simulation.
- The team is spending money developing FASTSim when they could be using Autonomie. The funds could instead be used to update SERA. The team is not looking at PHEVs—this is a big weakness. From other presentations, PHEVs seem to already be part of Autonomie.
- The principal investigator is not familiar with the Autonomie model, which would provide more robust results. Furthermore, the project includes only DOE cost targets, not today's costs.

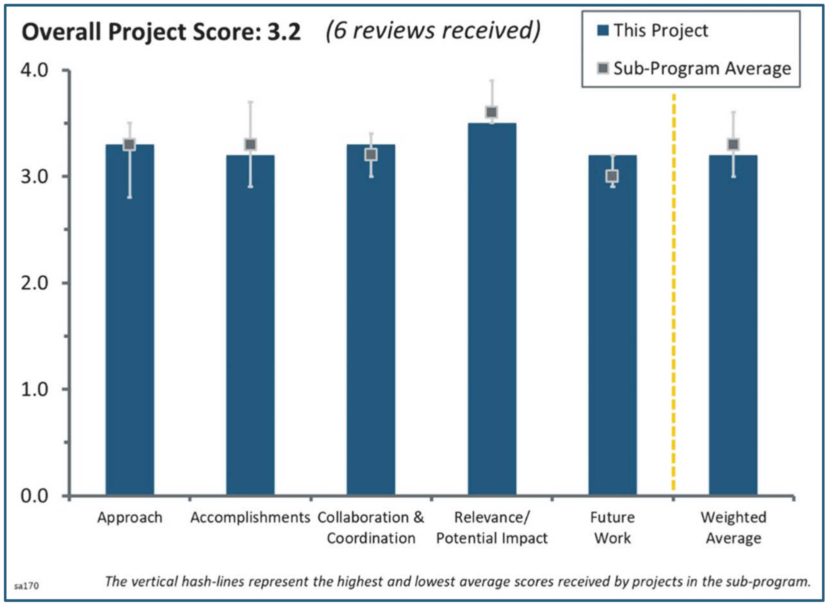
Recommendations for additions/deletions to project scope:

- The team should complete, or at least validate, the project with Autonomie results. It is recommended that the project team include current cost and compare with 2020 and 2040 R&D targets. The team should work with SERA to optimize the location of hydrogen refueling stations for these vehicle classes and include idling time.
- The team could possibly consider holding a brief discussion with Anheuser–Busch and get feedback on this work, since the company has recently placed an order for several hundred Nikola Motor Company hydrogen fuel cell trucks.
- The project team should replace FASTSim with Autonomie and include PHEVs. A sensitivity analysis should be performed. The team should vet the project assumptions and results for conventional vehicles with VTO and U.S. DRIVE.

Project SA-170: Analysis of Cost Impacts of Integrating Advanced Onboard Storage Systems with Hydrogen Delivery

Amgad Elgowainy; Argonne National Laboratory

Brief Summary of Project:



This project seeks to evaluate the impact of onboard hydrogen storage systems on delivery and refueling costs. Argonne National Laboratory, in collaboration with the U.S. DRIVE Partnership: Hydrogen Interface Taskforce, Lawrence Livermore National Laboratory, and Energy Technology Analysis, is addressing inconsistent data, assumptions, and guidelines by developing new delivery and refueling pathways in the Hydrogen Delivery Scenario Analysis Model (HDSAM) for onboard systems. By improving understanding regarding refueling pathways for onboard hydrogen storage and providing better models and tools to better evaluate relevant sustainability impacts, the project team aims to accelerate development and deployment of cost-effective refueling pathways.

Question 1: Approach to performing the work

This project was rated **3.3** for identifying and addressing barriers, project design, feasibility, and integration with other efforts.

- The project team evaluated three alternative storage concepts versus the baseline concept, compressed tank storage. The team focused on preliminary estimates of the key cost differences, with the proper emphasis on identifying overall trends and not the nitty-gritty details at this stage.
- The approach is to assess the cost impact of varying pressure and temperature conditions for a variety of onboard hydrogen storage temperatures. The team used modifications of existing Hydrogen Analysis (H2A) modeling/HDSAM tools and off-line modeling to assess the impact to refueling costs.
- This project appropriately identifies the approach necessary for the task.
- The approach is a good start, but it does not include key aspects (e.g., redesign of the dispensers and controls; onboard storage cost, volume, and mass impacts; or impacts on soft costs such as permitting, standoff distance, and site availability). Those areas should at least be acknowledged, even if they are not analyzed. If the principal investigator (PI) had discussed the approach in more detail, instead of using the first five minutes of his presentation to discuss challenges with 700 bar storage, this score would probably have been higher.
- The vehicle weight from added heat exchangers and metal hydrides would have an impact on weight. This needs to be evaluated with a vehicle model—perhaps through Autonomie or the Future Automotive Systems Technology Simulator (FASTSim). The metric of choice should cover the service envelope of miles traveled and not just dollars per kilogram of dispensed hydrogen.
- It would be good to understand key characteristics of materials-based storage, such as heat capacity.

Question 2: Accomplishments and progress

This project was rated **3.2** for its accomplishments and progress toward overall project and U.S. Department of Energy (DOE) goals.

- The team has demonstrated an objective and comprehensive assessment of the impacts of various proposed storage/refueling scenarios. The results are meant to be comprehensive in that they are not sub-optimizing, but rather are attempting to assess all impacts, positive and negative. Several systems were preliminarily examined: only the metal hydride system showed a pathway to significant net refueling cost reduction. The other pathways showed little to no improvement.
- The project team has done thorough analysis for the approach undertaken.
- The accomplishments align well with the stated goals of the analysis.
- The project started in October 2017, and progress to date is excellent in terms of concept definition and preliminary economics.
- The preliminary results were very interesting and suggested that metal–organic framework (MOF) systems may impose a large cost on the station. It was not clear whether the tank cooling was done for the MOF and cryogen-compressed tanks. The cryogen-compressed tanks can be cooled over repeated fills, but the MOF system does need additional cooling for each fill. This should be investigated if it is included.
- It was very difficult to identify the level of detail used for the analysis and how that level was selected, based on the slides provided. It appears that cost analysis was performed for only several primary components (the compressor and storage systems) and that the cooling system cost estimate was based only on the cost of energy. All other costs were assumed to be constant. Even the compressor and storage systems seem to have been analyzed using only a rough cost estimate. Those directions are probably acceptable; however, the reasoning and decisions behind them needed to be communicated.

Question 3: Collaboration and coordination

This project was rated **3.3** for its collaboration and coordination with other institutions.

- The project team's has excellent collaboration with Ford Motor Company, U.S. DRIVE tech teams, Energy Technology Analysis, Lawrence Livermore National Laboratory, and three other national laboratories with the needed expertise, as a result of prompt and thorough input provided by the collaborators.
- Direct input from original equipment manufacturers with cars on the road is very important. Even if it is not the primary input, reviewer input and perspective would be useful. The project team has considered many design choices.
- The project collaborations have resulted in sufficient input and a critical review of the results. The accomplishments are well presented and provide a relevant analysis of the task objectives.
- The list of collaborators on the project is appropriate, and they function as excellent information resources.
- It is good to see that the project team reached out to many key researchers from the Hydrogen Storage Engineering Center of Excellence. Given that BMW was developing a cryogen-compressed hydrogen storage system, it is recommended that the researchers contact the company to see whether BMW considered the impacts on the filling station when deciding about the company's storage technology. Given that there are several companies that have installed hydrogen filling systems, the researchers could have reached out to them for any lessons learned or could have looked at their approaches and results as a check.
- The list of collaborators is useful, and the project team consists of a good group. However, the team does not include members that could provide insights into alternative compressor costs and other options. Including them would help.

Question 4: Relevance/potential impact

This project was rated **3.4** for its relevance to/potential impact on supporting and advancing progress toward the Hydrogen and Fuel Cells Program goals and objectives delineated in the Multi-Year Research, Development, and Demonstration Plan.

- The project aligns extremely well with the Multi-Year Research, Development, and Demonstration Plan objectives. This project has the potential to advance progress toward DOE goals and objectives because delivery cost for hydrogen fuel is still a major cost item for fuel cell electric vehicles.
- The project fundamentally seeks to better understand the potential for refueling cost reduction via enactment of various approaches. Gaining understanding is vital to achieving cost reduction.
- As infrastructure developers consider cost reduction strategies, this task, the analysis, and the results provide a straightforward summary of potential options.
- It is always good to reevaluate technology options as laboratory breakthroughs come to fruition.
- This was an analysis that was needed years ago. The results need to be vetted with industry and validated in some manner. The question is how DOE is going to use this information.
- It is not clear where DOE's priorities are regarding onboard storage beyond compressed gas. Focusing on only the off-board aspects of the storage costs makes it very difficult to understand how these technologies might fare when considering the full cost of driving. It would help to link this analysis effort with results from the Hydrogen Storage sub-program category projects that focus on onboard storage using these materials. Since the technical potential for these technologies was not presented, it is hard to understand why they were analyzed.

Question 5: Proposed future work

This project was rated **3.2** for its proposed future work.

- Most results to date are marked as preliminary. Thus, future tasks will presumably finalize the estimates. Multiple narrow approach changes/expansions are listed, which together will ensure a comprehensive analysis when completed.
- The proposed activities are very logical continuations of this year's activities.
- The proposed future work continues the positive impacts of this project.
- The proposed future work looks like a good set of tasks to decrease the error bars around the analysis. The question is whether the current level of uncertainty encompasses competitive and promising technologies.
- The only recommendation is for the project team members to clarify how they plan to validate and vet their results.
- The combined cost and performance of delivery-dispensing onboard storage is more critical than the other proposed work. A major weakness of this analysis is that it does not include (or propose) any link to onboard storage analysis.

Project strengths:

- This is a much-needed analysis. The project team is looking at a key area that could influence the direction of onboard hydrogen storage projects at DOE. The team is very experienced, and the software modeling tools look to be appropriate.
- This is an outstanding analysis topic with a sound approach and a highly qualified PI and partners. There is excellent progress and collaboration with experts.
- The project has a well-experienced team that serves as an honest broker to comprehensively assess the refueling impact of various approaches.
- The researchers behind this analysis are very well versed in the topic and are well connected to industry.
- The project is well scoped, well executed, and well communicated.
- This is a good project, but it would be much better if it included some estimates of onboard storage and provided current status and future potential for each technology analyzed.

Project weaknesses:

- There is no overall weakness.
- The fundamental weakness of the project is that it has not identified significant pathways to refueling cost reduction. The cost breakdowns illustrated in the opening slide ($6–$8/kg for refueling cost) are for small-scale stations (only 200–300 kg/day). However, the costs shown later in the assessments of individual approaches are for 1000 kg/day stations.
- This project should include estimates of onboard storage and provide current status and future potential for each technology analyzed to help put the whole cost in context.
- Vehicles need to be considered to provide impact to the total cost of ownership for transportation.
- The project team needs to explain the plan to validate the results.

Recommendations for additions/deletions to project scope:

- The process for selecting technologies and identifying the level of analysis detail for each is not stated explicitly; this should be added to the project. If the technology selection process indicates that detailed analysis should be performed, then that should be within the scope. A rough estimate showing the impacts of delivery and refueling costs is necessary to understand whether they fit into the scope. Also, a rough estimate showing potential impacts of components (heat exchangers, liquid nitrogen storage and pump, etc.) is necessary to show the value of additional analysis on the components. All additional pathways should have a qualitative assessment of their potential value before detailed analysis is performed.
- The project team should consider adding a transportation analysis entity or develop in-house expertise with vehicle models.
- The cost of onboard storage must also be considered.

2018 Hydrogen and Fuel Cells Program Review Summary

This Appendix shows the results of the Hydrogen and Fuel Cells Program-level peer review for the 2018 Annual Merit Review (AMR), including feedback from a sub-set of the reviewers attending the AMR. A total of 70 Program-level reviewers were invited to provide feedback, and 26 reviewers responded.

1. General: The Hydrogen and Fuel Cells Program has a mission and strategy that are clearly articulated and has appropriate goals and milestones as well as quantitative metrics that are SMART (Specific, Measurable, Actionable, Relevant, and Timely).

Please comment on the overall Hydrogen and Fuel Cells Program as well as each sub-program, as appropriate. (Note: The Technology Acceleration sub-program includes the prior-year sub-programs Technology Validation, Manufacturing R&D, and Market Transformation.)

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

	Hydrogen and Fuel Cells Program Overall Rating	Hydrogen Production and Delivery R&D Sub-Program Rating	Fuel Cell R&D Sub-Program Rating	Hydrogen Storage R&D Sub-Program Rating	Technology Acceleration Sub-Program Rating	Safety, Codes and Standards Sub-Program Rating	Fossil Energy Solid Oxide Fuel Cell Sub-Program Rating
Average Score	8.8	8.6	8.3	8.6	8.4	8.7	8.1
Number of Responses	25	21	19	15	19	17	14

Comments:

- Congratulations are in order for the Fuel Cell Technologies Office (FCTO) director for bringing the Hydrogen and Fuel Cells Program (the Program) to its most exciting state, with the greatest potential in years. The involvement of the Hydrogen Council speakers in the plenary program was valuable. Congratulations to the DOE Office of Energy Efficiency and Renewable Energy (EERE) and Office of Fossil Energy (FE) for developing relevant and urgent programs.
- The Department of Energy's (DOE's) Program is excellent, since it clearly sets the cost target.
- The general focus of the various initiatives is in line with the long-term needs of the fuel cell industry.
- Overall, the work is excellent, with proper focus on reducing cost.
- With regard to the Safety, Codes and Standards (SCS) sub-program, the work is valuable, relevant, and timely. However, specificity and measurability within the goals is a bit lacking. Within the Fuel Cell R&D sub-program, there remains a bit of uncertainty as to the overall direction for finally achieving all of the technical sub-program targets simultaneously. This particular sub-program seems to have stalled in recent years, and it seems that the direction is not clear. Greater specificity is likely necessary within this sub-program to help it move closer toward its goals. Finally, the efforts regarding infrastructure and hydrogen production seem to be comprehensive and well formulated.
- The DOE Program mission and strategy are exemplary for the rest of the world. However, the Hydrogen Storage R&D sub-program was rated a bit lower than the others because the focus on hydrogen-in-materials solutions for applications is still too strong. This dimension is definitely a source of remarkable

scientific achievements, but it cannot continue to be labeled as a promising storage solution; the technological indicators have not improved in many years.

- The focus should be on renewable energy as much as possible.
- Increasing balance-of-plant (BOP) fundamental R&D is recommended. There is too much emphasis on platinum-group-metal-free (PGM-free) catalysts; over 20 years of R&D in this area has been unsuccessful. There is a question as to what percentage of the cost-per-kilowatt analysis (SA-James) is PGM compared to the total system cost, not just stack cost. Perhaps that should be the percentage of funds for alternative catalysts.
- The meaning of "early-stage research" in the context of the various sub-programs needs to be clarified, as does how "early-stage research" applies to hydrogen and fuel cells versus combustion and fossil fuels. It is not clear that the definition is applied consistently.

2. The Hydrogen and Fuel Cells Program is well focused and managed, and is effectively fostering research and development (R&D) to enable innovation and advance the state of technology for hydrogen and fuel cell technologies to be competitive and achieve widespread commercialization and deployment by industry.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	8.5
Number of Responses	24

Comments:

- The recent direction to develop programs through consortia appears to be a particularly effective method of managing the Program's research directions and sharing findings and knowledge. The ability to leverage greater resources within stakeholder organizations that complement FCTO's capabilities is also effective. This appears to be a well-designed Program management development.
- The market would not be where it is without DOE R&D. Continued investment is needed.
- The technical/scientific knowledge and competence of the sub-program managers is admirable.
- Congratulations are in order on international involvement and collaboration at the highest levels.
- The Program team does a very effective job of managing the sub-programs.
- As a general cautionary comment, a robust modeling toolkit is certainly an asset. However, proposed analysis projects should be screened to avoid analysis overkill. It is important to determine whether every analysis objective in the proposed project addresses a rate-limiting knowledge need (given the time horizon considered). Furthermore, the modeling project workflow template should incorporate industry/adopter reviews as a standard element (this was not depicted on the relevant slide of poster SA02). An "in-flight" review from end-use adopters would likely add value to the projects.

3. The Hydrogen and Fuel Cells Program's portfolio of projects is appropriately balanced across research areas to help achieve the Program's mission and goals and complements private sector, state, and other non-DOE investments.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	8.0
Number of Responses	24

Comments:

- The Program's portfolio of projects is balanced, and all aspects of hydrogen are covered. Polymer electrolyte membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), and others are covered for many applications.
- It is good to see how the Program has evolved over the years to maintain a strong impact on the market uptake of fuel cell and hydrogen technologies.
- It would be helpful to include in the plenary session of the AMR a presentation relating how projects are chosen, prioritized, and funded based on Administration input, FCTO strategy, review feedback from previous years, etc.
- The key areas of future development needs are HydroGEN; H2@Scale is effectively addressing key long-term needs. Also, manufacturing efforts and key component R&D are essential for future success.
- The balance is strong; however, the market could benefit from more focus on applying new technology to the market.
- The SOFC projects are focused either on core technology innovations or on large distributed power generation on the megawatt scale. Commercial application of fuel cell technology and its advancement into the mainstream requires special focus.
- Overall, the directions of the research Program are in line with the needs of stakeholders. However, the current restriction that deters projects geared toward implementation and late-stage R&D has the potential to significantly limit the relevance of the Program overall (acknowledging that this restriction is essentially imposed on FCTO by Congress). It does appear that even within this restriction, there may be opportunities to undertake more projects in line with implementation and growth in technology commercialization, given that these efforts within the fuel cell and hydrogen communities are firsts of their kind. Not much is known about consumers, market responses, and industry transformations that could provide key answers for large-scale fuel cell and hydrogen implementation. Therefore, it is suggested that the Program think creatively about justifications for projects that will be increasingly relevant as jurisdictions communicate first-of-their-kind information needs for making these technologies a reality.
- Manufacturing and BOP R&D are underfunded.

4. The Hydrogen and Fuel Cells Program's R&D aligns well with industry and stakeholder needs. Please comment on the overall Hydrogen and Fuel Cells Program as well as each sub-program, as appropriate.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

	Hydrogen and Fuel Cells Program Overall Rating	Hydrogen Production and Delivery R&D Sub-Program Rating	Fuel Cell R&D Sub-Program Rating	Hydrogen Storage R&D Sub-Program Rating	Technology Acceleration Sub-Program Rating	Safety, Codes and Standards Sub-Program Rating	Fossil Energy Solid Oxide Fuel Cell Sub-Program Rating
Average Score	8.2	8.3	7.8	8.6	7.9	8.2	7.7
Number of Responses	24	21	18	16	19	17	14

Comments:

- Program leadership is available to industry and stakeholders and is generally responsive to discussions about which projects will be helpful.
- Congratulations are in order to DOE EERE and FE for bringing important stakeholders into the Program. There should be cooperation in using the SOFC as a range extender in large hydrogen vehicles.
- An increased focus on deployment would be helpful. That said, the Program continues to provide tremendous benefit.
- The Program underemphasizes BOP and manufacturing R&D. The Program also ignores the cost of power conditioning; however, this will be important for commercialization.
- Some of the catalysis parallel projects seem to overlap in their objectives.

5. The Hydrogen and Fuel Cells Program is funding high-impact projects that have the potential to significantly advance the state of technology for the hydrogen and fuel cells industry. Please comment on the overall Hydrogen and Fuel Cells Program as well as each sub-program, as appropriate.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

	Hydrogen and Fuel Cells Program Overall Rating	Hydrogen Production and Delivery R&D Sub-Program Rating	Fuel Cell R&D Sub-Program Rating	Hydrogen Storage R&D Sub-Program Rating	Technology Acceleration Sub-Program Rating	Safety, Codes and Standards Sub-Program Rating	Fossil Energy Solid Oxide Fuel Cell Sub-Program Rating
Average Score	8.3	8.4	8.1	8.3	8.3	8.5	7.7
Number of Responses	24	20	17	14	18	16	16

Comments:

- The Hydrogen Production and Delivery sub-program, in particular, appears to present the opportunity to have a large, lasting impact on the development of hydrogen and fuel cell industries in the United States. The sub-program addresses several technical gaps simultaneously and is appropriately focused on the cost reduction of hydrogen for the ultimate consumer.
- The existing portfolio of pre-commercial approaches to cost reduction (particularly low-PGM systems) is a crucial component of the portfolio. The focus on reducing manufacturing process cost (roll-to-roll efforts) is also important.
- There are many high-impact projects within DOE FE and EERE, including projects concerning SOFCs, fuel cell electric vehicles (FCEVs), SOFC hybrids, EERE's H2@Scale, etc.
- The focus of the various sub-programs addresses primary issues/opportunities.
- The projects are relatively smaller than similar ones in other parts of the world. Perhaps some overarching projects with a strong (and guaranteed) multi-annual budget and a broader challenge portfolio could allow for intrinsically better coordination and stronger impact.

6. In your opinion, what were the most significant accomplishments within the Hydrogen and Fuel Cells Program during the past year? Please consider the entire AMR content and entire DOE portfolio, including poster sessions, rather than the plenary talks alone.

Please respond for any program area as appropriate (Hydrogen Production and Delivery, Storage, Fuel Cells, Technology Acceleration, Systems Analysis, Safety, Codes and Standards, Solid Oxide, ARPA-E, Basic Science, etc.).

Please state areas requiring more attention or improvement. If you do not have a response, please select "Not Applicable."

Comments:

- This is a hard question to answer, as the Program does many important things. From the perspective of establishing large-scale value proposition, some highlights are:
    - Systems analysis work (supply/demand curve)
    - Codes and standards work on nozzles and other station infrastructure, enabling hydrogen refueling station (HRS) rollout
    - Compatibility of pipeline materials and related codes and standards work to enable large-scale infrastructure
- These comments focus on the Safety, Codes and Standards sub-program, because this was the area allocated to the reviewer for this AMR. This sub-program has made small but important incremental progress. An example of this is H2Tools, built over many years but always up to date, providing much support and service, not only to the United States but also to the whole international community. An example of a one- to two-year accomplishment is the Sandia National Laboratories study of LH_2 behaviors and the new attention to public infrastructure.
- Different consortia (the Fuel Cell Consortium for Performance and Durability [FC-PAD], the Hydrogen Materials Advanced Research Consortium [HyMARC], etc.) were established a few years ago; this year, their relevance and effectiveness could be seen. Encouraging networks around a core team allows for concentration on a particular topic with a mid-term view and the capitalization of accomplishments; this is much more difficult when done only through projects.
- Accomplishments include the enhancement of the H2@Scale concept and the projects' collaboration with stakeholders, including Japan's Ministry of Economy, Trade and Industry (METI)/New Energy and Industrial Technology Development Organization (NEDO).

- It is critical to have a continued focus on electrolyzer technology improvement and reduced hydrogen delivery/station cost. An example is increasing the vehicle tank temperature to allow for an increase in the cooling temperature, ideally to 0°C, rather than the current -40°C.
- The highlights are accomplishments related to the Hydrogen Production and Delivery sub-program, the Safety, Codes and Standards sub-program, and the H2@Scale concept; these are driving hydrogen/fuel cell commercialization.
- The Program's key accomplishments were the progress in H2@Scale (hydrogen production and delivery), the volume manufacturing developments, and technology at scale.
- The most significant accomplishment is within the Safety, Codes and Standards sub-program; contributions to the codes development process are critical to the advancement of the hydrogen industry.
- Accomplishments include established collaborations with the Hydrogen Council members and many others.
- Some significant accomplishments include the Hydrogen Safety Panel's collaboration with internationally acclaimed organizations, as well as the plans moving forward.
- The reviewer works in the area of SOFCs and believes the plans for industry teams to demonstrate 200 kW prototypes are the most significant aspect of the Program.
- The adoption of H2@Scale has been crucial and will continue to be so through time.
- The Program has made progress in SOFCs and solid oxide electrolysis cells (SOECs).
- Projects particularly worth noting include (1) the characterization of electrolyzer performance in grid-tied operation to demonstrate the capability for grid balancing and grid services, (2) the characterization of liquid hydrogen vent plume fluid flow, (3) the evaluation of FCEV competitiveness compared to plug-in electric vehicles (PEVs) on various vehicle platforms, and (4) the characterization of hydrogen production potential across the United States. However, the Fuel Cell R&D sub-program has not exhibited significant advancement toward the ultimate technology targets for some time. It is acknowledged that the work in this sub-program requires perhaps a greater deal of basic research and, therefore, more time to achieve its goals than the other sub-programs. However, the Program does need to show more advances than it has recently.
- The FCTO's success in developing patents is commendable. Of the 255 patents developed by national laboratories, it would be helpful to know how many have been incorporated into fuel cell systems or the manufacture of fuel cell systems. This number could really show the value of national laboratory contributions and the importance of fundamental R&D. An emphasis on product water removal from thin-film catalyst layers could greatly enhance the value of ultralow-PGM catalyst layers. It would be good to address how transfer of product water to the anode can be improved, as well as look into new low-cost methods for corrosion protection of bipolar plates with high-rate deposition of protective coatings.

7. The R&D supported by the overall Hydrogen and Fuel Cells Program is appropriate in light of private-sector investments.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	8.0
Number of Responses	23

Comments:

- Based on the presentations and posters at the AMR:
  - FCTO's core R&D portfolio is entirely pre-commercial work—this is appropriate.
  - There is modest support for early-stage work in the private sector (e.g., the Small Business Innovation Research program)—this is also appropriate.
- At this time, the focus on the Hydrogen Production & Delivery sub-program and H2@Scale is most appropriate in terms of supporting commercialization.
- The stage and topics of R&D support the White House's early-stage applied research focus, which supports near-term economic growth.
- The supported R&D is based on industrial expectations and thus appears appropriate.
- Additional emphasis is recommended on high-rate manufacturing with reduction of stack conditioning times.
- It seems that private industry has recently been making several advancements in the areas covered by the Fuel Cell R&D sub-program. Moreover, the existing gaps appear to require developments that may be accomplished by continued engineering and science often within the bounds of industry efforts. This is the only Program area where future developments appear like they may be more industry-led, and the DOE Program may not be on as effective of a path.
- It is very difficult for this specific reviewer to have a clear and detailed enough picture of the various budget streams to answer this question. There is also a discrepancy between the figures resulting from the budget allocated to projects and the figures given in the plenary sessions, which focus exclusively on annual budget. In comparison to previous versions, this year's AMR has been less transparent.
- It is difficult these days to find private capital to fund longer-term developmental efforts, and the key enterprises in the fuel cell space simply do not have the capital to make these longer-term investments.
- The market would benefit from taking more DOE research and bringing it to market with seed funding. A number of great ideas are in need of help getting to scale.
- Until economics improve, it will be difficult for industry to commercialize these technologies.

8. The R&D supported by the Solid Oxide Fuel Cell sub-program is appropriate in light of private-sector investments.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Average Score	8.3
Number of Responses	12

Comments:

- The stage and topics of R&D support the White House's early-stage applied research focus, which supports near-term economic growth. There should be cooperation between SOFC efforts in natural gas and electric vehicle focus areas.
- While SOFC applications are further along from a commercial standpoint, it is important for the sub-program to have continued DOE support.
- SOFCs are an important technology option and should clearly be actively pursued.

9. Early-Stage Research and Development: The Hydrogen and Fuel Cells Program is focused on early-stage R&D as aligned with Administration objectives for federal research funding. Please provide suggestions for early-stage R&D that the Hydrogen and Fuel Cells Program should consider for promoting its goals and objectives.

Comments:

- It is recommended the Program continue research on hydrogen production methods with low lifecycle emission impacts (such as renewable or nuclear electrolysis), with the goal of making such production methods more cost-competitive.
- The early-stage R&D already in progress concerns key non-PGM catalysts and investigations of transitions to a higher rate of manufacturing of key stack components. Some activity into metallic plate and corrosion issues is suggested.
- The existing robust portfolio of early-stage research is appropriately aligned with this objective (e.g., low-PGM systems, alternative fuel systems [ammonia, dimethyl ether [DME], photoelectrochemical [PEC]).
- The Program covers almost all the topics to be investigated.
- There are several fundamental and basic questions about energy sector transitions and the successful implementation of those transitions that are currently unanswered. While not early-stage hard-science- or technology-based research, the questions are still early-stage because there does not appear to be a robust set of literature that points to definitive strategies for success, accounting for the technological, economic, and social behavior variables at play. It is recommended that these types of studies fall under the Technology Acceleration sub-program.
- An emphasis on product water removal from thin-film catalyst layers could greatly enhance the value of ultralow-PGM catalyst layers. The Program should address how transfer of product water to the anode could be improved, as well as new low-cost methods for corrosion protection of bipolar plates with high-rate deposition of protective coatings.
- The reviewer requests that FCTO and DOE consider the fact that some “bridging” effort in technology readiness levels (TRLs) 2–5 needs to remain to ensure that new research results reach the commercial pipeline.
- The Program should consider heavy-duty FCEV fueling and storage alternatives for H35 (in addition to cryogenic-compressed hydrogen, but not metal–organic frameworks [MOFs]).
- Focus may be directed to the industrial use of hydrogen, such as in steel manufacturing, refineries, and ammonia production.
- The Program should consider renewable hydrogen production, as well as medium- and heavy-duty applications.
- Early-stage R&D could include more collaboration with basic sciences in selected areas.
- The FE program should reestablish its focus on CO_2 reduction.
- Technology development efforts targeting the widespread usage of SOFCs, both in commercial and residential applications, require an impetus in order to create a pathway for lowering costs.
- Renewable hydrogen production is fundamental to success—and there is much research to be done.

10. Energy Materials Network (EMN) Consortia: Do you have any comments or recommendations on the Hydrogen and Fuel Cell Program's EMN consortia approach? Please state what is working effectively and areas that may benefit from further improvement. If you do not have a response, please select 'Not Applicable.'

Comments:

- The R&D consortia appear to be one of the more effective directions for Program management in recent years. In particular, the collaboration opportunities provided by these consortia seem effective and able to advance widespread commercial adoption in the future. So far, these consortia have been focused particularly on energy materials. However, it seems the general concept could be leveraged for other aspects of the FCTO Program. For example, questions of grid integration potential are largely information gaps for many stakeholders across the country that have similar questions but varying conditions, and likely varying solutions. Still, solutions and insights gained in individual applications of the concept and the surrounding research may inform other efforts. FCTO should consider how it can expand the consortia approach, especially the knowledge-sharing aspect, beyond materials research.
- The consortia approach is the best approach for long-term success and investment in R&D.
- This area is fully covered.
- The creation of the Energy Materials Network (EMN) is relevant and will allow cross-fertilization of materials knowledge. The main challenge might be effective coordination with the already existing consortia.

11. H2@Scale: What are the strengths and weaknesses of the H2@Scale initiative? Do you have any recommendations for other H2@Scale research topics or recommendations to enable the scale up and value proposition of H2@Scale (e.g. a region with low electricity prices, excess curtailment, and hydrogen supply opportunity along with a co-located demand for hydrogen, etc.)? Please provide any other recommendations on H2@Scale. If you do not have a response, please select 'Not Applicable.'

Comments:

- The H2@Scale initiative is one of the most important government concepts in the area of energy. The initiative's strength is embedded in the range of applications it covers. To enable the scale-up and value proposition of H2@Scale, it is recommended the initiative coordinate with industries that use hydrogen.
- The H2@Scale initiative's strength is focusing DOE attention on scaling hydrogen. It is necessary to have a focus on connecting hydrogen to the grid in a way that enables renewable energy penetration at an economically attractive rate.
- The H2@Scale initiative is timely and appropriate. It is necessary to compare electric and hydrogen infrastructure as complete energy conversion networks.
- H2@Scale is key, as the industry tells us that one of the limiting factors to greater fuel cell adoption is fuel production distribution and cost.
- The strengths of the H2@Scale initiative are its timeliness, relevance, and comprehensiveness. H2@Scale is an absolute necessity at this moment, when jurisdictions in the United States are transitioning to fully commercial FCEV and hydrogen markets and are looking to provide examples and templates for development that other jurisdictions across the country can follow. The potential weakness is that the questions are so complex that, as an initiative, H2@Scale likely requires careful and constant attention in program management to ensure focus and continued drive toward the end goal, which should be the ubiquitous use of hydrogen as a transportation fuel, enabled by low production and delivery cost (which is also aided by the expansion of hydrogen usage in other markets and sectors). One potential area for

additional research that the initiative does not yet seem to cover concerns the technologies and/or strategies for the massive scale of hydrogen storage and transportation that will be necessary to meet the goals of H2@Scale. As noted by the initiative and other domestic analyses of the potential for hydrogen fuel demand in the future, the amount of hydrogen envisioned within H2@Scale is far greater than today's production capacities. Moreover, hydrogen will need to be more fungible and transportable than today's hydrogen typically is, given the large proportion that is captive on-site hydrogen in the petroleum industry. How this hydrogen will be stored and moved around, particularly at this scale, seems to be a largely unanswered question.

- Starting with the creation of an evidence base is a very good approach to supporting the role that hydrogen and fuel cells can have in energy and transport systems. The bottom-up approach followed for this early stage is positive and adequate. Further support could be allocated to the H2@Scale initiative, especially to support larger demonstration flagship projects that focus on how hydrogen solutions can support the decarbonization of energy and transport systems. It is suggested that the Technology Acceleration sub-program projects be framed with the H2@Scale initiative as examples to replicate to accelerate the market penetration of fuel cell and hydrogen solutions.
- An important enabler for H2@Scale will be the ability for commercial entities to have access to wholesale/ very low-cost electricity. Currently, with the way utilities are regulated, this is not typically possible. Another enabler is the capital cost of electrolyzers; both cell-level research and system-level work similar to the dispensing infrastructure area could help.
- The initiative should demonstrate grid enhancement/support from colocation of hydrogen production, storage, and fuel cells with wind and solar so as to get hydrogen into the minds of organizations (such as non-government organizations) that push for other renewable technologies.
- The H2@Scale concept plays a very important role in creating networks with various stakeholders; however, it is weak in cooperation with basic research.
- H2@Scale is a nice approach that includes many usages of hydrogen. However, the reason for not including building heating and energy is not clear.
- Hydrogen should be evaluated in all aspects to maximize its role in the United States and the world: low-CO_2 energy.
- It is important to collaborate globally with stakeholders and strengthen the hydrogen supply chain.
- The H2@Scale market assessment effort is a critical underpinning to the rest of the Program. However, it is flawed in its present scope. It is critical that the H2@Scale market assessment effort incorporate broader sensitivity analysis across multiple input parameters. The credibility of the analysis (to this reviewer's dismay) is jeopardized by overly optimistic input assumptions for hydrogen generation, particularly regarding electrolyzer capital costs—$100/kW is likely not a reasonable baseline scenario. Capacity factor and electricity price are also key inputs, for which a range of values should be surveyed and prominently presented. Four scenarios (as briefly shown in the oral presentation) are not adequate. The project should be sufficiently resourced for more robust sensitivity analysis; otherwise, the results will lose credibility.
- Surprisingly, this year did not demonstrate a clear and strong strategic link between the initiative and decarbonization goals. This may be linked to the changed political landscape, but nevertheless, it is not clear how the hydrogen solution to the mentioned challenges is supposed to have a chance against existing/ other energy storage solutions, if it is not strategically linked to the decarbonization of all energy systems.
- Grid connection requirements are set by power companies, and existing fuel cell manufacturers recognize that grid connect is in fractions of a second. An independent analysis of the grid connect potential for electrolysis is needed.
- Because of the potential for private industry research laboratory engagement, this initiative should include laboratories other than national laboratories.

12. Collaboration: The Hydrogen and Fuel Cells Program is collaborating with appropriate groups of stakeholders. Please add any additional comments particularly on which stakeholders (e.g. academia, companies, small businesses, types of industries, etc.) should be more engaged and in what manner.

Please rate your response on a scale of 1 through 10, with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or N/A if you have no opinion. Please add any additional comments.

Please also provide recommendations for how the Hydrogen and Fuel Cells Program can better coordinate R&D with other offices in the U.S. Department of Energy (e.g., Office of Fossil Energy, Office of Nuclear Energy, Office of Science, ARPA-E, etc.), as well as with entities outside the U.S. Department of Energy (e.g. states, other agencies, industry, etc.).

Average Score	8.2
Number of Responses	24

Comments:

- Appropriate collaboration appears to be a Program-wide strength of FCTO. There has rarely been a project within the Program that appears not to have the appropriate group of collaborators.
- Engagement with key stakeholders for scale-up is substantive and a key Program element; therefore, collaboration (e.g., engagement with industrial gas companies, utility companies) should continue to be a proactive Program focus. Key industry stakeholder engagement (input and review) should be a standard and an explicitly scoped element of project development and execution. In particular, industry engagement should be a key element of the scope of fiscal year (FY) 2019 activities in infrastructure development and energy systems integration. The Program staff do quite a bit of this informally and through workshops, regular working calls with counterparts, etc.; this comment is to ensure that engagement is pursued fully and consistently.
- Coordination with other agencies in support of grid stability/reliability and H2@Scale seems to be most valuable. In particular, it is important to understand how to better integrate nuclear energy and perhaps work with state and regional utility regulators to enable integration of H2@Scale concepts.
- Increased collaboration is a key element of staying competitive in the longer term. Ideally, there would be more industry participation at the product, system, and application levels.
- The perspective of end users could have been more present in the AMR meetings for some of the Technology Acceleration sub-program projects (this comment is based on attended sessions). DOE may also want to consider having specific sessions in which projects (especially those that demonstrate a proof of concept) can directly address investors (e.g., by having a pitching session to potential investors). This could be done as part of the AMR.
- The H2@Scale presentation identifies hydrogen demand across the United States but does not make clear how much of that demand is presently satisfied by existing production or how much new production is necessary.
- The majority of focus seems to be with academia rather than the industry. Greater collaboration is suggested with FE and the DOE Office of Science.
- Coordination on SOFC R&D programs between ARPA-E, FE, and EERE is recommended.
- It would be helpful to have DOE as a full member of relevant associations.

13. International Collaboration: The Hydrogen and Fuel Cells Program collaborates through a number of international partnerships. For example, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is an international partnership to coordinate activities on hydrogen and fuel cells across 18 countries and the European Commission. The U.S. is assuming the chair role for IPHE in 2018. Please comment on actions DOE in conjunction with IPHE can undertake or activities that are effective/need improvement to accelerate progress in hydrogen and fuel cell technologies. If you do not have a response, please select 'Not Applicable.'

Comments:

- There are significant gaps in understanding the differences and similarities between approaches to fostering hydrogen and fuel cell advances and industry development across the globe. For example, the various countries that have initiated hydrogen fueling network development for FCEVs have, for the most part, adopted differing strategies. There is a lack of information and assessment regarding the effectiveness of these varying strategies, as well as opportunities for sharing insights between jurisdictions. International coordination on sharing information is necessary to help ensure continued success.
- It is necessary to be an "insider" to be able to detect the visible impact of work performed by IPHE. It is certainly a challenge for the United States, as the new chair, to increase impact and visibility, perhaps by modifying the modus operandi or even proposing new terms of reference and linking IPHE work to other international initiatives, such as Mission Innovation.
- The United States, specifically DOE, has been extremely forthcoming in presenting the results of its R&D investments and programs; it is not clear that other countries provide the general public with nearly the same level of information about results of their R&D investments.
- IPHE has definitely played key roles in promoting/implementing governmental policies. It is important to connect IPHE's activities with the Hydrogen Energy Ministerial Meeting in October.
- IPHE is too high level and limited because of political positioning during meetings. For example, in terms of the relationship between certain country interests, one will attempt with great difficulty to leave another out wherever possible. Thus, practical action items that can be committed to are necessary.
- Any work in the Safety, Codes and Standards sub-program, for example, that can contribute to harmonized regulations/standards is valuable.
- Regarding regulations, code and standards, safety aspects, and awareness-raising, the IPHE could support coordination among international actors and eventually support market acceleration and acceptance.
- DOE could ensure and facilitate an efficient exchange of global knowledge related to technology cost and performance, economically promising use cases, technical standards, and any other enablers.
- DOE's help is needed to communicate and translate success across different regions.
- International collaboration is of high importance. Nations are at difference stages in different areas, and all can help one another.
- Technology sharing in both directions—from and to the United States—should be emphasized.
- It is important to organize safety and regulation by international information exchange.

14. Prizes: Agencies have shown interest in implementing prizes and competitions as a mechanism to complement the conventional grant process. Examples include the H-Prize (H2Refuel) for a small-scale hydrogen fueling appliance that complements large retail stations. Please provide comments on the prize/competition approach and provide any suggestions for future prizes or competitions that would align with the goal of accelerating the widespread success of hydrogen and fuel cell technologies. If you do not have a response, please select 'Not Applicable.'

Comments:

- The prize approach is useful as one of a variety of strategies to encourage innovation in achieving Program goals. It is of high value to have a continued focus on driving down the cost of dispensing infrastructure.
- The prize for achievement is a good approach for recognizing key accomplishments and progress.
- It is recommended that the prize be focused on affordable renewable hydrogen production.
- A hydrogen prize for the application of PEMFCs in ocean-going ships is suggested.
- Prizes motivate many people.
- Perhaps there should be an H2@Scale Technology Transfer Award to recognize the successful commercialization of key technologies/use cases. Automakers have achieved this for FCEVs (with the introduction of production models), and big oil/station developers are on track with HRSs, yet other puzzle pieces remain (implementing economically favorable hydrogen feed-in to natural gas, grid integration, etc.).
- Hopefully, prizes help advance technology, although there is a bit of skepticism.
- Although this approach was good for spurring innovation in technologies that might have niche applications, industry was not entirely focused. The total market potential for the H2Refuel prize-winning technology is currently unclear; therefore, it is unclear whether the H-Prize program is an effective means of bringing technology to a market that was perhaps otherwise neglected. If further prize-based competitions are to be developed in the future, they should focus on solutions that (1) appear to need primarily engineering innovation rather than more basic science innovation and (2) meet a near-term gap in the available commercial products.
- This reviewer is against prizes, in particular if demonstrations have to be realized to earn a prize. Indeed, this means that project teams need a strong treasury to pay for the demonstration, and the funds may not be recovered if the team is not awarded. Such an approach is acceptable for industry but not for research entities. It may lead to favoring "rich" organizations, whereas good ideas can come from all.
- The concept of prizes is discouraged, as it has the ability to become too political.

15. Please comment on the overall strengths and weakness of the Hydrogen and Fuel Cells Program and its portfolio of projects. Please provide strengths and weaknesses for each sub-program as appropriate. On which technology areas should the Hydrogen and Fuel Cells Program put more or less focus for future activities? If you do not have a response, please select 'Not Applicable.'

Comments:

- The Program benefits from active review of progress being made, for example, at AMRs. There is a strong commitment to national laboratories, with many laboratories having projects that continue for decades. It is recommended that national laboratories have their projects competitively bid with other non-national-laboratory projects. Some of the most important technology, fuel cell, and electrochemical breakthroughs have come from industry, e.g., Nafion® and high-surface-area PGM catalysts, dimensionally stable electrodes, high-temperature electrochemistry, etc.

- For sub-program areas investing in R&D to explore liquefaction as a potential cost-reduction strategy for hydrogen production, delivery, and/or storage, it would be helpful also to analyze the energy and environmental impacts of liquefaction. If the process is energy-intensive, it could affect the well-to-wheels emissions of hydrogen and reduce the expected benefits relative to fossil fuels.
- FCTO's work has been great in terms of successfully establishing the best portfolio of projects with cost-targeting, including early-stage R&D and H2@Scale.
- The H2@Scale initiative is welcomed. The integration of market acceleration projects in this initiative could bring benefits.
- All areas within the Program are strong.
- The Program has been largely effective at advancing fuel cell and hydrogen technology toward the requirements identified in the Technology Roadmap, and the Program deserves great credit for this. However, within this success, the Fuel Cell R&D sub-program (specifically research on improving cell durability and other metrics) seems to need a new approach to continue providing meaningful advancements. The sub-program has recently adopted part of the consortium approach, and hopefully, this will usher in some progress that has not been present in that sub-program in recent years; however, if this, too, remains slow, a deeper restructuring may be needed. For future activities, H2@Scale and associated hydrogen production projects and activities should remain a priority for FCTO. In addition, safety, codes and standards work, especially work that helps address on-the-ground needs for improved science to inform standards and enable more widespread hydrogen fuel adoption, should remain a priority.
- Infrastructure R&D (identified as a FY 2019 priority) should be guided to some degree by the systems analysis work, in particular, the careful evaluation of regional markets and demand sectors in order to identify key stakeholders and region-specific infrastructure needs. Therefore, it is concerning to see the Systems Analysis line item reduced to $1 million for FY 2019 (from $3 million in FY 2018). Otherwise, the increased focus on infrastructure is potentially exciting, as long as it is scoped with substantial input from key private-sector enablers (e.g., oil majors, industrial gas handlers, potential demand sectors).
- In general, the sub-programs are addressing valuable topics. However, there are many subjects in total, so it might be worth prioritizing them to improve the overall focus (perhaps more resources on fewer high-priority projects). Also, a key strength of the overall Program is the test methods and test facilities that have been put into place. A focus is recommended on leveraging the use of those methods/facilities by other projects and by industry.
- The Program is well structured and coordinated. Its main strength is the evolution toward more basic research (TRL≤3). This is a real opportunity to prepare for the future through scientific and technological breakthroughs. However, this could also result in a weakness if having fewer demonstration projects decreases the connection with the industry (to which these findings are helpful).
- The reviewer's priority for adding faster adoption is to focus on hydrogen production delivery and distribution as a primary need. A secondary priority is continued investment in longer-term technology for stack components and higher-volume manufacturing strategies.
- Increased focus and budget are recommended on high-temperature electrolysis and energy storage using solid-oxide-based technologies.
- Fossil energy should have less focus. Instead, the focus needs to be on renewable and carbon-free energy that can help reduce climate-changing emissions.
- The research from the Fuel Cell R&D sub-program was fairly weak this year. The DOE laboratories were all in lockstep, pondering a single theory of oxygen resistance in electrodes. While the laboratories might feel that they are stronger united, it is not clear that they have latched onto the right theory and instead gave the appearance of groupthink, which is not conducive to cutting-edge research. The recognition that the accelerated stress tests mandated by DOE do not replicate the degradation of PtCo catalysts in the 2017 Toyota Mirai was quite a revelation. It is apparent (and noted by a speaker) that Toyota used the controls to meet performance goals. It might make more sense for the laboratories to report materials properties so that

all controls engineers can design around the materials properties. Instead, the laboratories are more focused on materials discovery. It seems that a focus on materials properties might be more productive overall.

16. Do you have any other comments or suggestions to improve the overall effectiveness of the Hydrogen and Fuel Cells Program or any of its specific sub-programs? If you do not have a response, please select 'Not Applicable.'

Comments:

- Overall, this is a very good program with excellent researchers and management.
- The work of FCTO and its sub-programs is extremely valuable and is helping to push hydrogen and fuel cells, especially in transportation, to successful commercial reality. Current Administration policy aside, the Program may need to start thinking about how to be most effective in a market and technology transition phase, rather than a market launch phase, within the next 5–10 years. Otherwise, the Program may risk having limited ability to remain as effective as it is today. Therefore, the current Administration's restrictions on the type of research conducted by the Program should also be reversed, such that the Program managers can most effectively tailor the projects to evolving stakeholder needs rather than an arbitrary limitation.
- There are no general suggestions. Instead, there is a comment regarding a detail of the AMR organization, which could improve the overall reviewing methodology: there was often not enough time available for reviewers to ask questions. It is recognized that a compromise is requested between many different boundary conditions, but often, the reviewers were not in the perfect position to assess a project because they could not ask some critical questions. It is proposed that those reviewers directly belonging to the FCTO team (thus having other occasions for understanding the projects) refrain from asking questions, or do so after the "external" reviewers (who have only a few minutes to understand a complex project) are finished.
- An increase in participation from the manufacturing industry as suppliers to the fuel cell industry is recommended. It is also important to balance funding between cell stack R&D and BOP R&D.
- There should be collaboration with FE on hydrogen production from coal and methane.
- The Program needs to have more focus on materials properties and less on materials discovery.

Attendee List: 2018 Hydrogen and Fuel Cells Program

Last Name	First Name	Organization
Abbasi	Reza	University of Delaware
Abdul Jabbar	M. Hussain	University of Maryland
Abernathy	Harry	National Energy Technology Laboratory
Aceves	Salvador	Lawrence Livermore National Laboratory
Ackroyd	Angie	Shell TechWorks
Adams	Jesse	U.S. Department of Energy
Adams	Kameron	U.S. Department of Energy
Adzic	Radoslav	Brookhaven National Laboratory
Afzal	Kareem	PDC Machines, Inc
Aguilo-Rullan	Antonio	Fuel Cells And Hydrogen Joint Undertaking (FCH JU)
Ahluwalia	Rajesh	Argonne National Laboratory
Ahmed	Alauddin	University of Michigan, Ann Arbor
Ahn	Channing	Caltech
Albertus	Paul	Advanced Research Projects Agency–Energy (ARPA-E)
Alia	Shaun	National Renewable Energy Laboratory
Allen	Jeff	National Institute of Clean and Low-Carbon Energy (NICE) America Research Inc. (China Energy)
Allen	Jeffrey	Michigan Technological University
Allendorf	Mark	Sandia National Laboratories
Alrashidi	Abdullah	University of Miami
Ambrozik	Stephen	National Institute of Standards and Technology
Anderson	Alfred	Greenway Energy LLC
Anson	Colin	University of Wisconsin–Madison
Antoni	Laurent	Commissariat à l'énergie atomique et aux énergies alternatives (CEA, French Atomic Energy Commission)
Aphale	Ashish	University of Connecticut
Ardo	Shane	University of California, Irvine
Aszklar	Henry	Franklin Park
Atanassov	Plamen	University of New Mexico
Austin	Camile	Idaho National Laboratory
Autrey	Tom	Pacific Northwest National Laboratory
Ayers	Katherine	Proton OnSite

Last Name	First Name	Organization
Bae	Byungchan	Korea Institute of Energy Research
Bae	Chulsung	Rensselaer Polytechnic Institute
Baek	Sean Sangjoo	Korea Institute of Energy Technology Evaluation and Planning (KETEP)
Bahar	Bamdad	Xergy Inc.
Baker	Alexander	Lawrence Livermore National Laboratory
Banham	Dustin	Ballard Power Systems
Banhardt	Volker	Freudenberg Performance Materials
Bant	Roy	Air Liquide
Barilo	Nick	Pacific Northwest National Laboratory
Barnett	Scott	Northwestern University
Barney	Scott	Millard County, Utah
Baronas	Jean	California Energy Commission
Bartolo	Bob	Transformational Liaisons (TRL), LLC
Basley	Austin	U.S. Department of Energy
Basu	Soumendra	Boston University
Baturina	Olga	U.S. Naval Research Laboratory
Bauer	Bernd	FUMATECH BWT GmbH
Baxley	Steve	Southern Company
Bea	Josep	Aperam Stainless Precision
Beckman	Mike	The Linde Group
Behling	Noriko	Kyushu University
Behm	Marvin	RCF Economic & Financial Consulting, Inc.
Belchuk	Mark	Freudenberg-NOK Sealing Technologies, Inc.
Bell	Robert	National Renewable Energy Laboratory
Belvin	Anthony	U.S. Department of Energy, Office of Nuclear Energy
Bender	Guido	National Renewable Energy Laboratory
Berry	Naveen	South Coast Air Quality Management District
Binder	Matthias	Greenerity GmbH
Bishop	Sean	Redox Power Systems
Blackburn	Bryan	Redox Power Systems
Blekhman	David	California State University, Los Angeles
Blieske	Matthew	Shell Global New Energies
Blum	John	Triton Systems
Boardman	Richard	Idaho National Laboratory

Last Name	First Name	Organization
Bonnaud	Aymeric	Naval Group
Borole	Abhijeet	Electro-Active Technologies, LLC
Borris	Robert	United States Postal Service
Borup	Rodney	Los Alamos National Laboratory
Bos	Albert	High yield Energy Technologies (HyET) Hydrogen
Boulanov	Dmitri	ArcelorMittal
Bouwkamp	Nico	California Fuel Cell Partnership/Frontier Energy
Bouwman	Peter	Nedstack
Bouza	Antonio	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Building Technologies Office
Bowden	Mark	Pacific Northwest National Laboratory
Bowman	Robert	Oak Ridge National Laboratory (retired)
Boyce	Kenneth	UL
Bran Anleu	Gabriela	Sandia National Laboratories
Braun	Robert	Colorado School of Mines
Braunecker	Wade	National Renewable Energy Laboratory
Broerman	Eugene	Southwest Research Institute
Brouwer	Jack	University of California, Irvine
Brown	George	The Chemours Company
Brown	Patrick	Southern California Gas Company
Bucci	Giovanna	Bosch Energy Storage Solutions
Budge	John	LG Fuel Cell Systems, Inc.
Burgess	Carroll	United States Postal Service
Burke	Patcharin	U.S. Department of Energy, National Energy Technology Laboratory
Burke	Susan	U.S. Environmental Protection Agency
Burns	James	University of Virginia
Burr	Stephanie	RCF Economic & Financial Consulting, Inc.
Buttner	William	National Renewable Energy Laboratory
Byham	Stephanie	The Building People/U.S. Department of Energy
Cai	Andrew	Case Western Reserve University
Calabrese Barton	Scott	Michigan State University
Caloprisco	Pietro	Fuel Cells and Hydrogen Joint Undertaking (FCH JU)
Capati	David	Toyota Motor North America

Last Name	First Name	Organization
Cappello	Joe	Iwatani Corporation
Capuano	Christopher	Proton OnSite
Carreiro	Louis	U.S. Naval Undersea Warfare Center, Division Newport
Carter	James	University of Nevada, Las Vegas, Department of Chemistry
Casey	Brendan	U.S. Naval Facilities Engineering Command (NAVFAC) Atlantic
Centeck	Kevin	U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)
Cervino	Victor	Mitsubishi Hitachi Power Systems Americas, Inc.
Chalk	Steve	U.S. Department of Energy
Chan	Shuk Han	U.S. Department of Energy
Chapman	Bryan	ExxonMobil
Chaudhuri	Santanu	Argonne National Laboratory
Cheekatamarla	Praveen	Atrex Energy, Inc.
Chen	Dejun	Georgetown University
Chen	Fanglin (Frank)	University of South Carolina
Chen	Kevin	University of Pittsburgh
Chen	Matthew	University of Toronto
Chen	Yu	Georgia Institute of Technology
Chen	Yun	West Virginia University
Cheng	Yuan	University of Pennsylvania
Chigusa	Sean	Tatsuno North America, Inc.
Cho	EunAe	Korea Advanced Institute of Science and Technology (KAIST)
Cho	Min Kyung	Hyundai Motor Company
Choi	Jung Pyung	Pacific Northwest National Laboratory
Chong	Lina	Argonne National Laboratory
Choudhury	Biswajit	E. I. du Pont de Nemours and Company (DuPont)
Christensen	John	National Renewable Energy Laboratory (consultant)
Christensen	Steven	National Renewable Energy Laboratory
Christian	Theresa	Exelon Corporation
Christner	Larry	Linear Growth Consulting, LLC (LGC)
Chung	Hoon	Los Alamos National Laboratory
Chung	T. C. Mike	Pennsylvania State University

Last Name	First Name	Organization
Clutterbuck	Amberlie	American Association for the Advancement of Science (AAAS)
Coker	Eric	Sandia National Laboratories
Cole	Carolyn	United States Postal Service
Colella	Whitney	Gaia Energy Research Institute LLC
Collins	William	WPCSOL, LLC (consultant)
Colon-Mercado	Hector	Savannah River National Laboratory
Connelly	Elizabeth	National Renewable Energy Laboratory
Contini	Vincent	MiTech Systems, Ltd.
Cordova	Jose	Mohawk Innovative Technology, Inc.
Corgnale	Claudio	Greenway Energy LLC
Corrigan	Dennis	DC Energy Consulting LLC
Corwin	Chris	Nexceris, LLC
Cox-Galhotra	Rosemary	Booz Allen Hamilton
Crawford	Lalida	U.S. Department of Energy
Creager	Stephen	Clemson University
Crum	Matthew	W. L. Gore and Associates
Cullen	David	Oak Ridge National Laboratory
Daehler	William	Delphi Electronics (retired)
Dale	Nilesh	Nissan Technical Center North America, Inc.
Damle	Ashok	Techverse, Inc
Daniel	Claus	Oak Ridge National Laboratory
Daniels	Jessica	U.S. Environmental Protection Agency
Danilovic	Nemanja	Lawrence Berkeley National Laboratory
Darling	RuthAnne	U.S. Department of Defense, Operational Energy
Dattelbaum	Andrew	Los Alamos National Laboratory
Davies	Peter Rhys	Honeywell Garrett SAS
Davis	Garret	Mohawk Innovative Technology, Inc.
DeBellis	Crispin	LG Fuel Cell Systems, Inc.
De Castro	Emory	Advent Technologies, Inc.
DeCuollo	Gerald	TreadStone Technologies, Inc.
De Guire	Mark	Case Western Reserve University
Deng	Chenxin	Case Western Reserve University
DeSantis	Daniel	Strategic Analysis, Inc.
Deshpande	Salil	The Building People

Last Name	First Name	Organization
Deutsch	Todd	National Renewable Energy Laboratory
Devlin	Pete	U.S. Department of Energy
DiGiuseppe	Gianfranco	Kettering University
Dimitrievska	Mirjana	National Renewable Energy Laboratory/National Institute of Standards and Technology
Ding	Dong	Idaho National Laboratory
Dinh	Huyen	National Renewable Energy Laboratory
Dirschka	Eric	NASA
Dismukes	Charles	Rutgers University
Dobbins	Tabbetha	Rowan University
Dogdibegovic	Emir	Lawrence Berkeley National Laboratory
Dolan	Michael	Commonwealth Scientific and Industrial Research Organization (CSIRO)
Dornheim	Martin	Helmholtz–Zentrum Geesthacht Centre for Materials and Coastal Research
Dosanjh	Bal	Ceres Power
Doshi	Jayesh	eSpin Technologies, Inc.
Dowd	Jeffery	U.S. Department of Energy
Driscoll	David	Glacigen Materials, Inc.
Drotleff	Kari	U.S. Army Tank Automotive Research, Development and Engineering Center
Drysdale	Glen	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
Du	Yanhai	Kent State University
Eckerle	Tyson	California Governor's Office of Business and Economic Development
Edwards	David	Air Liquide
Ehrhart	Brian	Sandia National Laboratories
Eisman	Glenn	Eisman Technology Consultants, LLC
Elangovan	S. Elango	OxEon Energy, LLC
Elrick	Bill	California Fuel Cell Partnership
Elsen	Heather	ExxonMobil Research and Engineering
Ettie	Gordon	Energy Scienomic
Eudy	Leslie	National Renewable Energy Laboratory
Ewan	Mitch	University of Hawaii, Manoa/Hawaii Natural Energy Institute
Fabian	Tibor	Ardica
Farhad	Siamak	University of Akron

Last Name	First Name	Organization
Fergus	Jeffrey	Auburn University
Fitzgerald	Nichole	Bioenergy Technologies Office
Flood	Gary	GSF Consulting, LLC
Florea	Radu	Honeywell Transportation Systems
Flowers	Daniel	Lawrence Livermore National Laboratory
Fontaine	Joseph	Naval Undersea Warfare Center Division Newport
Fortin	Stéphane	ENGIE
Fox	Melissa	Los Alamos National Laboratory
Franc	Pierre-Etienne	Air Liquide
Frank	David	Hydrogenics
Frank	Ed	Argonne National Laboratory
Freed	Mark	Anglo American
Frisk	Joseph	3M
Frois	Bernard	International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)
Frost	Mary	Duke Energy
Fukumoto	Takafumi	Nissan Technical Center N.A.
Fukunaga	Akihiko	JXTG Nippon Oil & Energy Co.
Furukawa	Takatoshi	Hino Motors
Gagliano	Joe	United Hydrogen
Gaillard	Nicolas	University of Hawaii
Galbach	Phillip	FedEx Express
Ganesan	Prabhu	Greenway Energy, LLC
Gardiner	Monterey	BMW Group
Garfunkel	Eric	Rutgers, The State University of New Jersey
Garland	Nancy	U.S. Department of Energy
Garman	Sarah	U.S. Department of Energy
Garsany	Yannick	Excet Inc./Naval Research Laboratory
Geiman	Laura	W.L. Gore & Associates, Inc.
Gennett	Thomas	National Renewable Energy Laboratory
Gervasio	Dominic Francis (Don)	University of Arizona
Ghezel-Ayagh	Hossein	FuelCell Energy, Inc.
Ghosh	Sourov	Great Wall Motor, China
Ghosh	Sujit	U.S. Department of Transportation, Maritime Administration
Gibbons	William	University of Maryland

Last Name	First Name	Organization
Ginovska	Bojana	Pacific Northwest National Laboratory
Girard	Francois	National Research Council Canada
Girardon	Pauline	APERAM
Gittleman	Craig	General Motors
Goldstein	Brian	Energy Independence Now
Gopalan	Srikanth	Boston University
Gordon	Bryan	Ivys Energy Solutions
Gore	Colin	Redox Power Systems
Gorensek	Maximilian	Savannah River National Laboratory
Gorlin	Yelena	Robert Bosch LLC
Gorte	Raymond J.	University of Pennsylvania
Goto	Risei	Sumitomo Corporation of Americas
Gottesfeld	Shimshon	University of Delaware, Chemical Engineering/Fuel Cell Consulting, LLC
Graetz	Jason	HRL Laboratories
Grassilli	Leo	U.S. Department of the Navy, Office of Naval Research (retired)
Greeley	Jeffrey	Purdue University
Green	Zachary	Giner, Inc.
Greene	David	University of Tennessee
Greene	Winfield	Giner, Inc.
Greenfield	Carl	International Technology and Trade Associates, Inc.
Gresalfi	Stephanie	General Services Administration
Groos	Ulf	Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE)
Gross	Markus	BMW Group
Gross	Thomas	Electricore, Inc.
Gross	Tom	Energy Planning and Solutions
Grot	Stephen	Ion Power
Groth	Katrina	University of Maryland
Gu	Taoli	Xergy, Inc.
Guerra	Omar J.	National Renewable Energy Laboratory
Gumeci	Cenk	Nissan
Gupta	Erika	U.S. Department of Energy, Fuel Cell Technologies Office
Gupta	Shalabh	Ames Laboratory

Last Name	First Name	Organization
Ha	Mai-Anh	National Renewable Energy Laboratory
Haak	Nico	SGL Carbon GmbH
Habibzadeh	Bahman	U.S. Department of Energy
Hackett	Gregory	U.S. Department of Energy, National Energy Technology Laboratory
Hamdan	Monjid	Giner ELX, Inc.
Hamilton	Jennifer	Frontier Energy/California Fuel Cell Partnership
Han	Minfang	Tsinghua University
Hanlin	Jason	Center for Transportation and the Environment
Hardis	Jonathan	National Institute of Standards and Technology
Hardy	Bruce	Savannah River National Laboratory
Hardy	John	Pacific Northwest National Laboratory
Harris	Aaron	Air Liquide
Harris	Alexander	Brookhaven National Laboratory
Harris	Kevin	Hexagon Lincoln
Harris	Lynn	North Carolina Department of Transportation, Rail Division
Harrison	Kevin	National Renewable Energy Laboratory
Harrison	William	NanoSonic Inc.
Hart	Richard	GE Global Research
Harting	Karen	Allegheny Science & Technology (AST)
Harvey	David	Fuel Cell Powertrain
Hatanaka	Tatsuya	Toyota Central R&D Labs., Inc.
Hattrick-Simpers	Jason	National Institute of Standards and Technology
Haug	Andrew	3M
He	Cheng	Washington University in St. Louis
Hecht	Ethan	Sandia National Laboratories
Heinselman	Karen	National Renewable Energy Laboratory
Heller	Claude	Air Liquide
Henk	Ramon	NOW GmbH
Heo	Tae Wook	Lawrence Livermore National Laboratory
Hering	Martin	Robert Bosch GmbH
Hicks	Brian	LG Fuel Cell Systems, Inc.
Hicks	Michael	H2 PowerTech, LLC
Higashi	Katsumi	Marubeni America Corporation

Last Name	First Name	Organization
Hinkley	James	Commonwealth Scientific and Industrial Research Organization (CSIRO)
Hinkley	Jim	Hinkley Consulting
Hinkly	Andrew	A P Ventures, LLC (APV)
Hirai	Shuichiro	Tokyo Institute of Technology
Hiraiwa	Chihiro	Innovation Core SEI, Inc.
Hirano	Shinichi	Ford Motor Company
Hirose	Katsuhiko	Toyota Motor Corporation
Ho	Donna	U.S. Department of Energy
Hoffrichter	Andreas	Michigan State University, Center for Railway Research and Education
Holby	Edward	Los Alamos National Laboratory
Holladay	Jamie	Pacific Northwest National Laboratory
Hopkins	Owen	Hexagon Composites
Houchins	Cassidy	Strategic Analysis, Inc.
Hovsapian	Rob	Idaho National Laboratory
Hu	Boxun	University of Connecticut
Hu	Shu	Yale University
Huang	Kevin	University of South Carolina
Huang	Yi-Lin	University of Maryland
Hulvey	Zeric	U.S. Department of Energy, Fuel Cell Technologies Office
Humanic	Paul	Nexceris, LLC
Hunter	Chad	National Renewable Energy Laboratory
Hupp	Joseph	Northwestern University
Hurst	Katherine	National Renewable Energy Laboratory
Hussey	Daniel	National Institute of Standards and Technology
Hwang	Robert	Sandia National Laboratories
Igarashi	Hiroshi	N.E. Chemcat Corporation
Ihnfeldt	Robin	General Engineering & Research
Iijima	Takashi	National Institute of Advanced Industrial Science and Technology
Iiyama	Akihiro	University of Yamanashi
Ikeji	Maki	Sumitomo Electric Industries, LTD
Ingram	Brian	Argonne National Laboratory
Irvin	Nick	Southern Company

Last Name	First Name	Organization
Irwin	Levi	ManTech International Corporation/ U.S. Department of Energy, Solar Energy Technologies Office
Isaac	Raphael	University of California, Davis
Ishida	Takanobu	Toyota Motor Corporation
Ishikawa	Katsuya	Kawasaki Heavy Industries, Ltd.
Ishizu	Yuta	Toyota Motor North America
Ito	Tadashi	Chiyoda Corporation
Izuhara	Daisuke	Toray Industries, Inc.
Izzo	John	U.S. Naval Undersea Warfare Center Division Newport
Jacobson	David	National Institute of Standards and Technology
Jadun	Paige	National Renewable Energy Laboratory
Jakupca	Ian	NASA
James	Brian	Strategic Analysis, Inc.
James	Bryan	University of Florida
James	Sean	Microsoft Corporation
Jang	Jong Hyun	Korea Institute of Science and Technology
Jankovic	Jasna	University of Connecticut
Jaramillo	Thomas	Stanford University
Jawahar Hussaini	Syed Mubeen	University of Iowa
Jaworski	Casey	Tanaka Kikinzoku International Inc.
Jenks	Cynthia	Argonne National Laboratory
Jensen	Craig	University of Hawaii
Jerram	Lisa	American Public Transportation Association
Jeske	Gerald	Umicore AG & Co. KG
Jia	Hongfei	Toyota Motor North America
Jin	Jason	Xergy, Inc.
Johnson	Gordon	New Jersey General Assembly
Johnson	Justin	National Renewable Energy Laboratory
Johnson	Terry	Sandia National Laboratories
Joseck	Fred	U.S. Department of Energy
Josefik	Nicholas	U.S. Army Corps of Engineers
Kallman	Richard	City of Santa Fe Springs, Department of Fire – Rescue
Kanazashi	Hisashi	Japan External Trade Organization (JETRO)

Last Name	First Name	Organization
Kanesaka	Hiroyuki	Fuel Cell Cutting-Edge Research Center Technology Research Association (FC-Cubic TRA)
Karabacak	Tansel	University of Arkansas at Little Rock
Karlsson	Tim	International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE)
Karpiak	Charles	United States Postal Service
Karstedt	Joerg	Zentrum für BrennstoffzellenTechnik (ZBT) GmbH
Kast	James	Toyota Motor North America
Kato	Hisao	Toyota Motor Corporation
Katsube	Yasuyuki	Sumitomo Corporation of Americas, Business Development Group
Kauffman	Douglas	U.S. Department of Energy, National Energy Technology Laboratory
Keller	Jay	Zero Carbon Energy Solutions (consultant)
Kenausis	Kristin	U.S. Environmental Protection Agency
Kent	Ronald	Southern California Gas Company/Sempra Energy
Kervitsky	George	KEE Consulting
Khan	Imran	National Renewable Energy Laboratory
Khatiwada	Suman	Syzygy Plasmonics
Kidner	Neil	Nexceris, LLC
Kim	Jai-Woh	U.S. Department of Energy, Office of Fossil Energy
Kim	Jungho	Kolon Industries, Inc.
Kim	Juyong	J & L Technology Group
Kim	Kiyoung	Ilsung Machinery Co., Ltd.
Kim	Sangil	University of Illinois at Chicago
Kim	Sang-Kyung	Korea Institute of Energy Research
Kim	Yu Seung	Los Alamos National Laboratory
Kimminau	David	Electrify America, LLC
Kimura	Tatsusaburo	Sumitomo Corporation
King	Nacole	U.S. Department of Energy
Kirby	Brent	Pacific Northwest National Laboratory
Kishimoto	Takeaki	Nisshinbo Holdings Inc.
Klahr	Benjamin	CNA Corporation
Klebanoff	Leonard	Sandia National Laboratories
Kleen	Greg	U.S. Department of Energy
Knights	Shanna	Ballard Power Systems

Last Name	First Name	Organization
Kobayashi	Masaya	Toyota Motor Corporation
Kobayashi	Yohei	Honda Engineering Co. Ltd.
Koeppel	Brian	Pacific Northwest National Laboratory
Koiwa	Nobuki	Honda R&D Co., Ltd.
Kondo	Shinji	Sumitomo Corporation
Kongkanand	Anusorn	General Motors, Fuel Cell Activities
Koonce	Michael	Luxfer-GTM Technologies, LLC
Kopasz	John	Argonne National Laboratory
Kort	Kenneth	U.S. Department of Energy, Advanced Manufacturing Office
Krause	Theodore	Argonne National Laboratory
Kreller	Cortney	Los Alamos National Laboratory
Kreutzer	Cory	National Renewable Energy Laboratories
Kumaraguru	Swami	General Motors
Kunze	Klaas	BMW Corporation
Kuroha	Tomohiro	Panasonic Corporation
Kuroki	Rentaro	Toyota Motor North America
Kurosaki	Daisuke	Chiyoda Corporation
Kurtz	Jen	National Renewable Energy Laboratory
Kusoglu	Ahmet	Lawrence Berkeley National Laboratory
LaFleur	Chris	Sandia National Laborotories
Lai	Ming-Chia	Wayne State University
Lalli	Jen	NanoSonic Inc.
LaManna	Jacob	National Institute of Standards and Technology
Lany	Stephan	National Renewable Energy Laboratory
Lara-Curzio	Edgar	Oak Ridge National Laboratory
Lausten	Mark	Allegheny Science & Technology, supporting U.S. Department of Energy, Solar Energy Technologies Office
Le	Xuan	Kraton Polymers
Leavitt	Mark	General Motors
Lee	Albert	Los Alamos National Laboratory
Lee	Dong Un	Stanford University
Lee	D-Y	Argonne National Laboratory
Lee	Sangwoo	Rensselaer Polytechnic Institute

Last Name	First Name	Organization
Lee	Won-Yong	Korea Institute of Energy Research, Zero-Energy Building
Leighton	Dan	National Renewable Energy Laboratory
Leighton	DeLisa	IGX Group/Luxfer-GTM Technologies
Leighty	William C.	The Leighty Foundation
Lepercq	Thierry	ENGIE
Levesque Tremblay	Gabriel	American Institute of Chemical Engineers (AIChE)
Levy	Michael	Aaqius
Li	Gong Liang	NGK Spark Plug Co., Ltd.
Li	Lin-Feng	Bettergy Corporation
Li	Wen	Tianneng Power International Co., Ltd.
Li	Wenyuan	West Virginia University
Li	Wenyue	American University
Li	Xianming Jimmy	National Institute of Clean and Low-Carbon Energy (NICE) America Research Inc.
Lim	Tae Won	Hyundai Motor Company
Lindell	Matthew	3M
Linkous	Clovis	Youngstown State University
Lipp	Ludwig	T2M Global
Litster	Shawn	Carnegie Mellon University
Liu	Di-Jia	Argonne National Laboratory
Liu	Dongxia	University of Maryland, College Park
Liu	Hong	Oregon State University
Liu	Hongtan	University of Miami
Liu	Jian	Polar Onyx
Liu	Meilin	Georgia Institute of Technology
Liu	Xingbo	West Virginia University
Liu	Zhien	LG Fuel Cell Systems, Inc.
Loe	Claire	Saint-Gobain
Lomax	Frank	Headwaters Solutions, LLC
Loosen	Suzanne	San Francisco Department of the Environment
Louderback	Benjamin	Idaho National Laboratory
Lousenberg	Robert	Compact Membrane Systems, Inc.
Ludlow	Daryl	Ludlow Electrochemical Hardware Corporation
Luo	Yusheng	Idaho National Laboratory
Lyubovsky	Maxim	U.S. Department of Energy

Last Name	First Name	Organization
Ma	Zhiwen	National Renewable Energy Laboratory
MacInnis	Jessica	University of Toronto
Maes	Miguel	NASA White Sands Test Facility
Maness	Pin-Ching	National Renewable Energy Laboratory
Mani	Prasanna	Proton OnSite
Mann	Margaret	National Renewable Energy Laboratory
Mao	Zq	Tsinghua University
Marcinkoski	Jason	U.S. Department of Energy
Maric	Radenka	University of Connecticut
Marina	Olga	Pacific Northwest National Laboratory
Marius	Noemie	National Renewable Energy Laboratory
Markovich	Steven	U.S. Department of Energy, National Energy Technology Laboratory
Marsh	Andrew	LG Fuel Cell Systems, Inc.
Martinez	Andrew	California Air Resources Board
Maruta	Akiteru	Technova Inc.
Marxen	Sara	CSA Group
Masel	Richard	Dioxide Materials
Mason	Chad	Advanced Ionics
Masten	David	General Motors
Mastropasqua	Luca	Princeton University
Matranga	Christopher	U.S. Department of Energy, National Energy Technology Laboratory
Matsumoto	Ayako	Mitsui & Co. Global Strategic Studies Institute
Matsutani	Koichi	Tanaka Kikinzoku Kogyo K.K.
Matter	Paul	pH Matter, LLC
Matzger	Adam	University of Michigan
Mauger	Scott	National Renewable Energy Laboratory
Maxwell	Deborah	BoMax Hydrogen, LLC
Mayyas	Ahmad	National Renewable Energy Laboratory
McCarroll	Larry	Alakai Technologies Corporation
McCoy	Britney	U.S. Environmental Protection Agency
McDaniel	Anthony	Sandia National Laboratories
McDougle	Stephen	MEI Technologies, Inc. (consultant to NASA White Sands Test Facility)
McKain	Rodger	LG Fuel Cell Systems, Inc.

Last Name	First Name	Organization
McKeown	Kyle	The Linde Group
McKone	James	University of Pittsburgh
McQueen	Shawna	U.S. Department of Energy, Fuel Cell Technologies Office
Meeks	Noah	Southern Company
Melaina	Marc	Great Wall Motors
Melczer	Thomas	Fuel Cell Powertrain
Mertes	Catherine	RCF Economic & Financial Consulting, Inc.
Mi	Zetian	University of Michigan, Ann Arbor
Miller	David	U.S. Department of Energy
Miller	Eric	U.S. Department of Energy, Fuel Cell Technologies Office
Miller	James	Argonne National Laboratory
Milliken	JoAnn	New Jersey Fuel Cell Coalition
Mills	Michael	Lawrence Berkeley National Laboratory
Minh	Nguyen	University of California, San Diego
Minhas	Sunny	Intertek
Mintz	Marianne	Argonne National Laboratory
Mishler	Jeffrey	Ardica Technologies, Inc.
Mitchell	John	BoMax Hydrogen, LLC
Mittelsteadt	Cortney	Giner, Inc.
Miyanabe	Kota	Iwatani Corporation
Mizroch	John	John F. Mizroch, LLC (JFM LLC)
Mizumoto	Kazuya	Honda R&D Co., Ltd.
Modestino	Miguel	New York University
Mohan	Ram	Singular Ventures LLP
Mohanpurkar	Manish	Idaho National Laboratory
Moore	Jared	Meridian Energy Systems
Moradi	Ramin	University of Maryland
Moran	Ed	Deloitte Consulting
More	Karren	Oak Ridge National Laboratory
Moreland	Greg	CSRA Inc., supporting Oak Ridge National Laboratory and the U.S. Department of Energy, Fuel Cell Technologies Office
Moretto	Pietro	European Commission Joint Research Centre (JRC)
Morgan	Brad	Tetramer Technologies, LLC

Last Name	First Name	Organization
Morgan	Jason	AvCarb Material Solutions
Moriya	Takashi	Honda R&D Co., Ltd.
Moriyama	Koji	Honda R&D Americas
Morris	Ashley	University of Kentucky, Center for Applied Energy Research
Morris	William	NuMat Technologies, Inc.
Motyka	Ted	Greenway Energy LLC
Mubeen	Syed	University of Iowa
Muhich	Christopher	Arizona State University
Mukerjee	Sanjeev	Northeastern University
Mukherjee	Ushnik	University of Waterloo
Mukundan	Rangachary	Los Alamos National Laboratory
Muna	Alice	Sandia National Laboratories
Murata	Soma	Japan External Trade Organization
Muromoto	Nobuyoshi	Honda Engineering Co., Ltd.
Murphy	Dani	National Renewable Energy Laboratory
Musgrave	Charles	University of Colorado Boulder
Myers	Charles	CSRA Inc./Oak Ridge National Laboratory
Myers	Deborah	Argonne National Laboratory
Nagai	Tomoyuki	Toyota Motor North America
Nakamura	Hiroshi	Fujiseiki Co., Ltd.
Nakazawa	Taichi	Nissan Chemical Corporation
Nam	Sang Yong	Gyeongsang National University
Natelson	Robert	Allegheny Science & Technology, supporting the U.S. Department of Energy, Bioenergy Technologies Office
Natesan	Nitin	The Linde Group
Nawoj	Kristen	U.S. Department of Energy
Nelissen	Gert	Borit NV
Newman	Aron	Booz Allen Hamilton
Neyerlin	Kenneth	National Renewable Energy Laboratory
Nguyen	Tien	Independent
Nicholas	Jason	Michigan State University
Nicollet	Clement	Massachusetts Institute of Technology
Nishigaki	Nobutoshi	Sumitomo Corporation of Americas
Nishimura	Shin	Kyushu University

Last Name	First Name	Organization
Nixon	Robin	U.S. National Park Service, National Mall and Memorial Parks
Notardonato	William	NASA Kennedy Space Center
Novotny	Clint	U.S. Department of Defense, Operational Energy
Novy	Melissa	Virginia Polytechnic Institute and State University (Virginia Tech)
O'Brien	James	Idaho National Laboratory
Ocampo	Minette	pH Matter LLC
Odgaard	Madeleine	EWII Fuel Cells
Odom	Sara	Electricore, Inc.
Oesterreich	Robert	Air Liquide
Ogitsu	Tadashi	Lawrence Livermore National Laboratory
Ogura	Fumiaki	Tanaka Kikinzoku Kogyo K.K.
O'Hayre	Ryan	Colorado School of Mines
Ohira	Eiji	New Energy and Industrial Technology Development Organization (NEDO)
Ohma	Atsushi	Nissan Motor Co., Ltd.
Ohnuma	Akira	Toyota Boshoku Corporation
Okamoto	Mineharu	Iwatani Corporation of America
Olson	Gregory	CSRA Inc. (consultant)
Onorato	Shaun	National Renewable Energy Laboratory
Osenar	Paul	Upstart Power, Inc.
Otgonbaatar	Uuganbayar	Exelon
Owejan	Jon	Alfred State, State University of New York (SUNY) College of Technology
Pak	Chanho	Gwangju Institute of Science and Technology
Pal	Uday	Boston University
Palm	David	Stanford University
Pan	Keji	Redox Power Systems, LLC
Pan	Mu	Wuhan University of Technology, China
Pan	Shuye	YAPP USA Automotive Systems, Inc.
Pandey	Amit	LG Fuel Cell Systems, Inc.
Papageorgopoulos	Dimitrios	U.S. Department of Energy
Pappas	Alex	U.S. National Park Service
Parilla	Philip	National Renewable Energy Laboratory
Park	Andrew	The Chemours Company

Last Name	First Name	Organization
Park	Gu-Gon	Korea Institute of Energy Research
Park	Hyun Seo	Korea Institute of Science and Technology
Park	Jihye	Hyundai Motor Company
Parkan	John Michael	Providence Entertainment
Parker	Eric	U.S. Department of Energy (Contractor)
Parra	Erika	MultiPHY Laboratories
Pasaogullari	Ugur	University of Connecticut
Patel	Pinakin	T2M Global
Patil	Kailash	Giner, Inc.
Pellow	Matthew	Electric Power Research Institute (EPRI)
Penev	Michael	National Renewable Energy Laboratory
Peng	Zhenmeng	The University of Akron
Perry	Mike	United Technologies Research Center (UTRC)
Pesaran	Alireza	University of Maryland
Peters	Michael	National Renewable Energy Laboratory
Peterson	David	U.S. Department of Energy, Fuel Cell Technologies Office
Petitpas	Guillaume	Lawrence Livermore National Laboratory
Pickles	Jeff	National Institute of Clean and Low-Carbon Energy (NICE) America Research Inc.
Pierre	Joseph	KeyLogic Systems, Inc.
Pietras	John	Saint-Gobain
Pietrass	Tanja	Los Alamos National Laboratory
Pike	Joseph	Nikola Motor Company
Pintauro	Peter	Vanderbilt University
Pitts	Larry	Plug Power
Pivovar	Bryan	National Renewable Energy Laboratory
Podkaminer	Kara	U.S. Department of Energy
Polevaya	Olga	Nuvera Fuel Cells, Inc.
Pollica	Darryl	Ivys Energy Solutions
Pomerantz	Michael	Bennett Pump Co.
Popovich	Neil	National Renewable Energy Laboratory
Portela Cubillo	Christine	Freudenberg Technology Innovation SE & Co.
Portela Cubillo	Fernando	Freudenberg Technology Innovation SE & Co.
Post	Matthew	National Renewable Energy Laboratory
Potyrailo	Radislav	General Electric

Last Name	First Name	Organization
Powell	Joseph	Shell Global
Prendergast	David	Lawrence Berkeley National Laboratory
Procter	Michael	Automotive Fuel Cell Automotive Corporation
Qiu	Yun	Environmental & Production Solutions
Quackenbush	Karen	Fuel Cell and Hydrogen Energy Association
Quedenfeld	Heather	U.S. Department of Energy, National Energy Technology Laboratory
Ramani	Vijay	Washington University in St. Louis
Rambach	Glenn	California State University, Bakersfield/Third Orbit Power Systems, Inc.
Ramsden	Todd	National Renewable Energy Laboratory
Randolph	Katie	U.S. Department of Energy
Read	Carole	National Science Foundation
Recknagle	Kurtis	Pacific Northwest National Laboratory
Reddi	Krishna	Argonne National Laboratory
Reed	Jeffrey	University of California, Irvine
Renz	Tobias	Tobias Renz FAIR
Ricketson	Sean	U.S. Department of Transportation, Federal Transit Administration
Ridell	Bengt	SWECO Energuide AB
Riley	Conor	National Renewable Energy Laboratory
Rinebold	Joel	Connecticut Center for Advanced Technology, Inc.
Rivkin	Carl	National Renewable Energy Laboratory
Robertson	Denzel	Air Liquide
Robles	Justo	Energy Independence Now
Rockward	Tommy	Los Alamos National Laboratory
Roeder	Jeffrey	Sonata LLC
Rogers	Paul	U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)
Rojas-Carbonell	Santiago	University of Delaware
Ronevich	Joseph	Sandia National Laboratories
Ross	Steven	U.S. Department of Energy
Rowe	Ian	U.S. Department of Energy
Roy	Derek	Elemental Resources LLC
Roychoudhury	Subir	Precision Combustion, Inc.
Rufael	Tecle	Chevron Energy Technology Company

Last Name	First Name	Organization
Rupnowski	Peter	National Renewable Energy Laboratory
Rustagi	Neha	U.S. Department of Energy, Fuel Cell Technologies Office
Ruth	Mark	National Renewable Energy Laboratory
Ryu	Hee Yeon	Hyundai Motor Company
Sakurahara	Kazuo	Honda R&D Co., Ltd.
San Marchi	Chris	Sandia National Laboratories
Sanchez	Joel	Stanford University
Sanders	Michael	Colorado School of Mines
Santucci	Christopher	Toyota Motor North America
Sasaki	Kotaro	Brookhaven National Laboratory
Sasakura	Masaharu	Institute of Applied Energy
Satomi	Tomohide	Fuel Cell Commercialization Conference of Japan
Sattler	Christian	German Aerospace Center (DLR)
Satyapal	Sunita	U.S. Department of Energy
Sauber	Peter	Peter Sauber Agentur
Saucedo	Alex	GenCell Energy
Saur	Genevieve	National Renewable Energy Laboratory
Savguira	Yuri	University of Toronto
Schenck	Deanna	U.S. Department of Energy, Fuel Cell Technologies Office
Schlasner	Steve	Energy and Environmental Research Center
Schlueter	Debbie	EWII Fuel Cells
Schmidt	Lasse	Volkswagen Group
Schneider	Jesse	Nikola Motor Company
Schneider	Martin	Hydrogenious Technologies GmbH
Schoentgen	Raphael	Hydrogen Advisors
Scholz	Andreas	Enrichment Technology Company Ltd.
Schöpping	Gerhard	Freudenberg Performance Materials Holding SE & Co. KG
Schramm	Scott	U.S. Army Tank Automotive Research, Development and Engineering Center (TARDEC)
Schumacher	Christian	U.S. Naval Undersea Warfare Center Division Newport
Schwartz	Viviane	U.S. Department of Energy, Basic Energy Sciences
Sedoglavich	Nemanya	Shell TechWorks
Seki	Yasuhiro	N. E. Chemcat Corporation

Last Name	First Name	Organization
Selman	Nancy	Skyre, Inc.
Semelsberger	Troy	Los Alamos National Laboratory
Serfass	Jeff	Hydrogen Education Foundation
Serov	Alexey	University of New Mexico, Center for Emerging Energy Technologies/Pajarito Powder, LLC
Setzler	Brian	University of Delaware
Severa	Godwin	University of Hawaii
Shao	Yuyan	Pacific Northwest National Laboratory
Shibata	Osamu	Mitsui & Co. (U.S.A.), Inc.
Shimpalee	Sirawit	Spring Valley High School
Shimpalee	Sirivatch	University of South Carolina
Shin	Dongwon	Korea Institute of Energy Research
Shinde	Subhash L.	University of Notre Dame
Shindo	Atsushi	Fujiseiki Co., Ltd.
Shreffler	Eric	Michigan Economic Development Corporation
Shulda	Sarah	National Renewable Energy Laboratory
Siegel	Donald	University of Michigan
Siegel	Kay Kimberly	H2Safe, LLC
Simmons	Daniel	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy
Simmons	Kevin	Pacific Northwest National Laboratory
Simotwo	Silas	Redox Power Systems
Singer	Suzanne	Lawrence Livermore National Laboratory
Singh	Brij	John Deere
Singh	Prabhakar	University of Connecticut
Singhal	Subhash	Pacific Northwest National Laboratory
Siriwardane	Rajani	U.S. Department of Energy, National Energy Technology Laboratory
Sishtla	Chakravarthy	Gas Technology Institute
Skandan	Ganesh	NEI Corporation
Smith	David	Oak Ridge National Laboratory
Smith	Owen	National Renewable Energy Laboratory
Smith	Richard	Hydrogen Energy Center
Smith	William	Infinity Fuel Cell and Hydrogen, Inc.
Snyder	Joshua	Drexel University

Last Name	First Name	Organization
Snyder	Seth	Idaho National Laboratory, Division of Clean Energy & Transportation
Sofronis	Petros	University of Illinois at Urbana-Champaign/ International Institute for Carbon-Neutral Energy Research (I^2CNER)
Soloveichik	Grigorii	Advanced Research Projects Agency–Energy (ARPA-E)
Song	Liang	Brookhaven National Laboratory
Song	Xueyan	West Virginia University
Sorensen	Paul	Shell TechWorks
Soto	Herie	Shell Oil Company
Spendelow	Jacob	Los Alamos National Laboratory
Sprik	Sam	National Renewable Energy Laboratory
Spurgeon	Joshua	University of Louisville
Srinivasamurthi	Vivek	De Nora
Stamenkovic	Vojislav	Argonne National Laboratory
Stavila	Vitalie	Sandia National Laboratories
Stechel	Ellen	Arizona State University, LightWorks
Steinbach	Andrew	3M
Steiner	Nadia	Université de Franche-Comté
Stetson	Ned	U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Fuel Cell Technologies Office
Stevenson	Jeff	Pacific Northwest National Laboratory
Stewart	Sarah	Robert Bosch Research and Technology Center
Stoffa	Joseph	U.S. Department of Energy, National Energy Technology Laboratory
Stoots	Carl	Idaho National Laboratory
Stottler	Gary	General Motors
St-Pierre	Jean	University of Hawaii, Manoa/Hawaii Natural Energy Institute
Suda	Kazuhiro	Honda Motor Co., Ltd
Sulic	Martin	Greenway Energy LLC
Suram	Santosh	Toyota Research Institute
Swanborn	Rombout	High yield Energy Technologies (HyET) group
Swartz	Scott	Nexceris, LLC
Sweet	Andrew	Giner, Inc.
Swider-Lyons	Karen	U.S. Naval Research Laboratory

Last Name	First Name	Organization
Taie	Zachary	Oregon State University – Cascades
Takaishi	Hideyuki	Takaishi Industry Co., Ltd.
Tamburello	David	Savannah River National Laboratory
Tamura	Nobuharu	Iwatani Corporation of America
Tang	Hua	University of California, Los Angeles
Tarver	Jacob	National Renewable Energy Laboratory
Teprovich	Joseph	California State University, Northridge
Terlip	Danny	National Renewable Energy Laboratory
Thomas	Sandy	Clean Car Options (retired)
Thompson	Peter	Hydrogen Education Foundation
Thompson	Simon	U.S. Department of Energy, Fuel Cell Technologies Office
Thornton	Matthew	National Renewable Energy Laboratory
Thorpe	Steven	University of Toronto
Toelle	Sascha	Umicore AG & Co. KG
Tong	Jianhua	Clemson University
Toriyama	Hiroki	Mitsubishi Corporation
Torun	Secil	ENGIE
Toughiry	Mark	U.S. Department of Transportation
Townsend	Justin	Oak Ridge Associated Universities (ORAU)
Toyota	Shohei	Honda R&D Co., Ltd.
Trejos	Vanessa	U.S. Department of Energy, Fuel Cell Technologies Office
Tsai	Li Duan	Industrial Technology Research Institute
Tsuchiya	Hiroshi	New Energy and Industrial Technology Development Organization (NEDO)
Tsuji	Yoichiro	Panasonic Corporation
Tsuyoshi	Manabu	Iwatani Corporation
Tucker	Michael	Lawrence Berkeley National Laboratory
Uddin	Aman	Carnegie Mellon University, Department of Mechanical Engineering
Ulsh	Michael	National Renewable Energy Laboratory
Usuda	Hiroyuki	New Energy and Industrial Technology Development Organization (NEDO)
Vail	Sean	Booz Allen Hamilton
Valente	Patrick	Ohio Fuel Cell Coalition
Vanderborgh	Nicholas	Los Alamos National Laboratory (retired)

Last Name	First Name	Organization
Veenstra	Mike	Ford Motor Company
Veith	Gabriel	Oak Ridge National Laboratory
Verduzco	Laura	Chevron Corporation
Vesely	Charles	Cummins Inc.
Vickers	James	U.S. Department of Energy, Fuel Cell Technologies Office
Vijayagopal	Ram	Argonne National Laboratory
Visconti	Kelly	U.S. Department of Energy
Vora	Shailesh	U.S. Department of Energy, National Energy Technology Laboratory
Vukmirovic	Miomir	Brookhaven National Laboratory
Wachsman	Eric	University of Maryland
Wagner	Emanuel	Hydrogen Education Foundation
Wakabayashi	Makoto	Nissan Chemical America Corporation
Walchuk	George	ExxonMobil Research and Engineering Company
Waldecker	James	Ford Motor Company
Wan	Zhaohui	Wuhan WUT New Energy Co., Ltd.
Wang	Chao	Johns Hopkins University
Wang	Chao	Pacific Northwest National Laboratory
Wang	Conghua	TreadStone Technologies, Inc.
Wang	Guofeng	University of Pittsburgh
Wang	Jia	Brookhaven National Laboratory
Wang	Lan	University of Delaware
Wang	Michael	Argonne National Laboratory
Wang	Wensheng	Atrex Energy, Inc.
Wang	Yun	University of California, Irvine
Ward	Patrick	Savannah River National Laboratory
Wasia	Charlotte	Idaho National Laboratory
Watanabe	Masahiro	University of Yamanashi
Weber	Adam	Lawrence Berkeley National Laboratory
Wegener	Jan	NOW GmbH
Wegeng	Robert	Pacific Northwest National Laboratory, Solar Thermochemical Advanced Reactor System (STARS)
Wei	Max	Lawrence Berkeley National Laboratory
Weidner	John	University of South Carolina

Last Name	First Name	Organization
Weimer	Alan	University of Colorado
Weisenberger	Matthew	University of Kentucky, Center for Applied Energy Research
Weng	Dacong	Honeywell Aerospace
Wheeler	Douglas	DJW Technology, LLC
Williams	Mark	AECOM and National Energy Technology Laboratory
Williamson	Sherman	United States Postal Service
Wilson	Adria	U.S. Department of Energy
Wilson	Josh	University of Louisiana at Lafayette
Wipke	Keith	National Renewable Energy Laboratory
Wocken	Chad	Energy & Environmental Research Center
Wood	Brandon	Lawrence Livermore National Laboratory
Wood	David	Oak Ridge National Laboratory
Woods	Stephen	NASA
Wu	Gang	University at Buffalo, State University of New York (SUNY)
Wu	Song	Mitsubishi Hitachi Power Systems Americas, Inc.
Wu	Wenzhuo	Purdue University
Xiang	Chengxiang (CX)	California Institute of Technology
Xie	Jian	Indiana University–Purdue University Indianapolis
Xing	Zhengliang	LG Fuel Cell Systems, Inc.
Xu	Hui	Argonne National Laboratory
Yamada	Keiko	Osaka Chamber of Commerce & Industry, Japan
Yamanis	John Jean	ElectroChem Ventures LLC
Yang	Zhiwei	United Technologies Research Center (UTRC)
Yelvington	Paul	Mainstream Engineering Corporation
Yildirim	Mustafa Hakan	EWII Fuel Cells
Yoshimura	Yui	Iwatani Corporation
Yousfi Steiner	Nadia	FCLAB/Labex ACTION
Zalis	Walter	Energetics
Zelenay	Piotr	Los Alamos National Laboratory
Zeng	Zhipeng	West Virginia University
Zenyuk	Iryna	Tufts University
Zhai	Shang	Stanford University
Zhang	Junliang	Shanghai Jiao Tong University (SITU)

Last Name	First Name	Organization
Zhang	Xu	University of Miami
Zhang	Xuyang	University of Miami
Zhao	Feng	Storagenergy Technologies, Inc.
Zhao	Haiyan	University of Idaho
Zhong	Yu	Worcester Polytechnic Institute
Zhou	Xiao-Dong	Academic
Zhu	Jiahong	Tennessee Technological University
Zhu	Tianli	United Technologies Research Center (UTRC)
Zimmerman	Jonathan	Sandia National Laboratories
Zou	Shouzhong	American University
Zulevi	Barr	Pajarito Powder, LLC

General Project Evaluation Form

This evaluation form was used for the following Hydrogen and Fuel Cells sub-program review panels/projects: Hydrogen Fuels (Hydrogen Production, Delivery, and Storage), Fuel Cells, Technology Acceleration (Manufacturing R&D; Safety, Codes and Standards; Technology Validation; Market Transformation; and Systems Analysis), and H2@Scale.

Evaluation Criteria: U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review

Please provide specific, concise comments to support your evaluation. It is important that you write in full sentences and clearly convey your meaning to prevent incorrect interpretation.

1. Approach

To performing the work – the degree to which project objectives and critical barriers have been clearly identified and are being addressed, and the extent to which the project is well designed, feasible, and integrated with other efforts. **(Weight = 20%)**

4.0 - Outstanding. Sharply focused on overcoming critical barriers; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Approach to performing the work:

2. Accomplishments and Progress

Toward overall project and DOE goals – the degree to which progress toward project objectives has been made and measured against well-defined performance indicators, and the degree to which the project has demonstrated progress toward addressing critical barriers to achieving DOE goals. **(Weight = 45%)**

4.0 - Outstanding. Outstanding progress towards project objectives is demonstrated through clear and measurable performance indicators; results have directly led to overcoming one or more critical barriers.
3.5 - Excellent. Excellent progress towards project objectives is demonstrated through clear and measurable performance indicators; results suggest that one or more critical barriers will be overcome.
3.0 - Good. Significant progress has been made, but there are weaknesses that need to be addressed to improve the rate of progress or improve the clarity of the project's objectives and performance indicators; contributes to overcoming some barriers.
2.5 - Satisfactory. Moderate progress has been made, but there are weaknesses that need to be addressed to improve the rate of progress or improve the clarity of the project's objectives and performance indicators; contributes to overcoming some barriers.
2.0 - Fair. Modest progress—rate of progress has been slow; may have some impact on overcoming barriers.
1.5 - Poor. Minimal progress towards project objectives and poorly defined performance indicators; unlikely to contribute to overcoming the barriers.
1.0 - Unsatisfactory. Little to no demonstrated progress toward project objectives; unlikely to contribute to overcoming the barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Accomplishments and Progress toward overall project and DOE goals:

3. Collaboration and Coordination with Other Institutions

The degree to which the project effectively engages and coordinates project partners and interacts with other entities and projects to accelerate project progress and improve the likelihood of the project's success and impact.
(Weight = 10%)

4.0 - Outstanding. Close, appropriate collaboration with other institutions; partners are full participants and well-coordinated.
3.5 - Excellent. Good collaboration; partners participate and are well coordinated.
3.0 - Good. Collaboration exists; partners are fairly well coordinated.
2.5 - Satisfactory. Some collaboration exists; coordination between partners could be significantly improved.
2.0 - Fair. A little collaboration exists; coordination between partners could be significantly improved.
1.5 - Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners.
1.0 - Unsatisfactory. No apparent coordination with partners.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Collaboration and Coordination with other institutions:

4. Relevance/Potential Impact

The degree to which the project supports and advances progress toward the Hydrogen and Fuel Cells Program goals and objectives, as delineated in the Multi-Year RD&D plan and/or the Program and sub-program overview presentations from the 2018 AMR. (Weight = 15%)

4.0 - Outstanding. Project is critical to the Hydrogen and Fuel Cells Program and has potential to significantly advance progress toward DOE RD&D goals and objectives.
3.5 - Excellent. The project aligns well with the Hydrogen and Fuel Cells Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives.
3.0 - Good. Most project aspects align with the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.5 - Satisfactory. Project aspects align with some of the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
2.0 - Fair. Project partially supports the Hydrogen and Fuel Cells Program and DOE RD&D objectives.
1.5 - Poor. Project has little potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.
1.0 - Unsatisfactory. Project has little to no potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Relevance/Potential Impact:

5. Proposed Future Work

The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. **Note:** if a project has ended, please leave blank. **(Weight = 10%)**

4.0 - Outstanding. Plans clearly build on past progress and are sharply focused on critical barriers to project goals; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers.
3.0 - Good. Plans generally build on past progress and should contribute to overcoming some barriers.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers.
2.0 - Fair. Plans may lead to improvements, but need better focus on addressing project weaknesses; may have some impact on overcoming barriers.
1.5 - Poor. Minimally responsive to project objectives; unlikely to resolve project weaknesses and contribute to overcoming barriers.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming barriers.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Proposed Future Work:

SUMMARY OF REVIEWER COMMENTS

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

HydroGEN Seedling Project Evaluation Form

This evaluation form is for use with HydroGEN seedling projects.

Evaluation Criteria: U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program Annual Merit Review

Please provide specific, concise comments to support your evaluation. It is important that you write in full sentences and clearly convey your meaning to prevent incorrect interpretation.

1. Approach

To performing the work – the degree to which barriers have been clearly identified, and are being addressed through project innovation; and the extent to which the project is well-designed, feasible, and integrated with the HydroGEN Consortium network. A strong emphasis should be placed on the appropriateness of the budget period 1 scope of work toward validation of the project's technology innovation. **(Weight = 20%)**

4.0 - Outstanding. Sharply focused on critical barriers and validating technology innovation; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers and validating technology innovation.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers and validating technology innovation.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers and validating technology innovation.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers and/or validating technology innovation.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers or validating technology innovation.
1.0 – Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers or validating technology innovation.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Approach to performing the work:

2. Relevance/Potential Impact

The degree to which the project supports and advances progress toward the DOE Hydrogen and Fuel Cells Program goals and objectives, and also supports the HydroGEN Consortium mission. A strong emphasis should be placed on the project's potential to advance the discovery and development of novel, advanced water splitting materials systems which will enable meeting the DOE ultimate hydrogen production goal of $2/kg H2. An additional factor to consider is how well the project fits into, leverages, and potentially enhances the framework and resources of the HydroGEN Consortium. **(Weight = 15%)**

4.0 - Outstanding. Project is critical to the Hydrogen and Fuel Cells Program and has potential to significantly advance progress toward DOE RD&D goals and objectives and is significantly leveraging and contributing to the resources and framework of the HydroGEN consortium.
3.5 - Excellent. The project aligns well with the Hydrogen and Fuel Cells Program and DOE RD&D objectives and has the potential to advance progress toward DOE RD&D goals and objectives and is aptly leveraging and contributing to the resources and framework of the HydroGEN consortium.
3.0 - Good. Most project aspects align with the Hydrogen and Fuel Cells Program and DOE RD&D objectives and the project is adequately leveraging and contributing to the resources and framework of the HydroGEN consortium.
2.5 - Satisfactory. Project aspects align with some of the Hydrogen and Fuel Cells Program and DOE RD&D objectives and the project is leveraging and contributing to the resources and framework of the HydroGEN consortium to some extent.
2.0 - Fair. Project partially supports the Hydrogen and Fuel Cells Program and DOE RD&D objectives and the project is not adequately leveraging and contributing to the resources and framework of the HydroGEN consortium.
1.5 - Poor. Project has little potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives and the project has minimal interaction with HydroGEN to leverage and contribute to the resources and framework of the HydroGEN consortium.
1.0 - Unsatisfactory. Project has little to no potential impact on advancing progress toward the Hydrogen and Fuel Cells Program and DOE RD&D goals and objectives and the project is not leveraging and contributing to the resources and framework of the HydroGEN consortium.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Relevance/Potential Impact:

3. Accomplishments and Progress

Toward overall project and DOE goals – the degree to which progress has been made and measured against performance indicators, and the degree to which the project has demonstrated progress toward DOE goals as well as the HydroGEN Consortium mission. A particular emphasis should be placed on the strength of the data presented by the accomplishments (including data from the HydroGEN nodes leveraged by the project) in terms of supporting accomplishments. An additional emphasis should be placed on the strength of the project's budget period 1 Go/No-Go Criteria and on project progress toward meeting this criteria. **(Weight = 30%)**

4.0 - Outstanding. Sharply focused on critical barriers with significant and convincing data to support the accomplishments towards ambitious Go/No-Go Criteria; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers and provides data that considerably supports the accomplishments towards impactful Go/No-Go Criteria.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers and provides adequate data to support accomplishments towards meaningful Go/No-Go Criteria.
2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers and provides some data to support accomplishments towards adequate Go/No-Go Criteria.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers and has limited data and accomplishments to support the Go/No-Go Criteria; Go/No-Go Criteria may be weak.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers and meet the Go/No-Go Criteria; Go/No-Go criteria is not adequate or missing.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers and meet the Go/No-Go Criteria; Go/No-Go criteria is not adequate or missing.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Accomplishments and Progress toward overall project and DOE goals:

4. Collaboration Effectiveness

With HydroGEN and, if applicable, other research entities – the degree to which the project has engaged with the HydroGEN EMN and has effectively used nodes to accelerate materials development and improve the likelihood of the project's success and impact. This also includes the effectiveness of project engagement with the broader materials research community, including work with HydroGEN's cross-cutting benchmarking/protocols (2b) project team, the HydroGEN Data Team, pathway-specific Working Groups, and others. An additional factor is the broader value and impact of the project's data sharing through the HydroGEN data hub. **(Weight = 25%)**

4.0 - Outstanding. Close, appropriate collaboration with other institutions, specifically the HydroGEN Consortium with appropriate use of nodes, contributions to the benchmarking/protocols (2b) project and the HydroGEN Data Hub; partners are full participants and well-coordinated.
3.5 - Excellent. Good collaboration, specifically the HydroGEN Consortium with appropriate use of nodes, contributions to the benchmarking/protocols (2b) project and the HydroGEN Data Hub; partners participate and are well-coordinated.
3.0 - Good. Collaboration exists with the HydroGEN Consortium and includes node utilization and engagement with the benchmarking/protocols (2b) project and the HydroGEN Data Hub; partners are fairly well-coordinated.
2.5 - Satisfactory. Some collaboration exists; coordination between partners could be significantly improved, specifically with respect to the HydroGEN Consortium node utilization activities, and engagement with the benchmarking/protocols (2b) project and the HydroGEN Data Hub.
2.0 - Fair. A little collaboration exists; coordination between partners could be significantly improved, specifically with respect to the HydroGEN Consortium node utilization activities, and engagement with the benchmarking/protocols (2b) project and the HydroGEN Data Hub.
1.5 - Poor. Most work is done at the sponsoring organization with little outside collaboration; little or no apparent coordination with partners and HydroGEN Consortium.
1.0 - Unsatisfactory. No apparent coordination with partners and HydroGEN Consortium.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Collaboration and Coordination with other institutions:

5. Proposed Future Work

The degree to which the project has effectively planned its future in a logical manner by incorporating appropriate decision points, considering barriers to its goals and, when sensible, mitigating risk by providing alternate pathways. Note: if a project has ended, please leave blank. **(Weight = 10%)**

4.0 - Outstanding. Sharply focused on critical barriers, meeting end-of-project goals and advancing the materials research mission of the HydroGEN Consortium; difficult to improve significantly.
3.5 - Excellent. Effective; contributes to overcoming most barriers, meeting most end-of-project goals and advancing the materials research mission of the HydroGEN Consortium.
3.0 - Good. Generally effective but could be improved; contributes to overcoming some barriers, meeting some end-of-project goals and has potential to advance the materials research mission of the HydroGEN Consortium.

2.5 - Satisfactory. Has some weaknesses; contributes to overcoming some barriers, meeting some end-of-project goals and may contribute to advancing the materials research mission of the HydroGEN Consortium.
2.0 - Fair. Has significant weaknesses; may have some impact on overcoming barriers, make minimal progress towards end-of project goals and insignificantly contributes to advancing the materials research mission of the HydroGEN Consortium.
1.5 - Poor. Minimally responsive to project objectives; unlikely to contribute to overcoming the barriers or meet end-of-project goals and will most likely not contribute to advancing the materials research mission of the HydroGEN Consortium.
1.0 - Unsatisfactory. Not responsive to project objectives; unlikely to contribute to overcoming the barriers or meet end-of-project goals and is unlikely to contribute to advancing the materials research mission of the HydroGEN Consortium.

- ☐ 4.0 - Outstanding
- ☐ 3.5 - Excellent
- ☐ 3.0 - Good
- ☐ 2.5 - Satisfactory
- ☐ 2.0 - Fair
- ☐ 1.5 - Poor
- ☐ 1.0 - Unsatisfactory

Comments on Proposed Future Work:

Project Strengths:

Project Weaknesses:

Recommendations for Additions/Deletions to Project Scope:

2018 Hydrogen and Fuel Cells Program Review Questions

1. General: The Hydrogen and Fuel Cells Program has a mission and strategy that are clearly articulated and has appropriate goals and milestones as well as quantitative metrics that are SMART (Specific, Measurable, Actionable, Relevant, and Timely).

Please comment on the overall Hydrogen and Fuel Cells Program as well as each sub-program, as appropriate. (Note: Technology Acceleration sub-program includes the prior year sub-programs Technology Validation, Manufacturing R&D, and Market Transformation.)

Please rate your response on a scale of 1 through 10 with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

	Strongly Disagree				**Neutral**				**Strongly Agree**		
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**NA**
Hydrogen and Fuel Cells Program Overall	○	○	○	○	○	○	○	○	○	○	○
Hydrogen Production and Delivery R&D Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Fuel Cell R&D Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Hydrogen Storage R&D Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Technology Acceleration Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Safety, Codes and Standards Sub-Program	○	○	○	○	○	○	○	○	○	○	○

Fossil Energy Solid Oxide Fuel Cell Sub-Program	○	○	○	○	○	○	○	○	○	○	○

Comments:

2. The Hydrogen and Fuel Cells Program is well focused and managed, and is effectively fostering research and development (R&D) to enable innovation and advance the state of technology for hydrogen and fuel cell technologies to be competitive and achieve widespread commercialization and deployment by industry.

Please rate your response on a scale of 1 through 10 with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

Strongly Disagree				Neutral			Strongly Agree			
1	2	3	4	5	6	7	8	9	10	NA
○	○	○	○	○	○	○	○	○	○	○

Comments:

3. The Hydrogen and Fuel Cells Program's portfolio of projects is appropriately balanced across research areas to help achieve the Program's mission and goals and complements private sector, state and other non-DOE investments.

Please rate your response on a scale of 1 through 10 with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

Strongly Disagree				Neutral			Strongly Agree			
1	2	3	4	5	6	7	8	9	10	NA
○	○	○	○	○	○	○	○	○	○	○

Comments:

4. The Hydrogen and Fuel Cells Program's R&D aligns well with industry and stakeholder needs. Please comment on the overall Hydrogen and Fuel Cells Program as well as each sub-program, as appropriate.

Please rate your response on a scale of 1 through 10 with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

	Strongly Disagree				Neutral			Strongly Agree			
	1	2	3	4	5	6	7	8	9	10	NA
Hydrogen and Fuel Cells Program Overall	○	○	○	○	○	○	○	○	○	○	○
Hydrogen Production and Delivery R&D Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Fuel Cell R&D Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Hydrogen Storage R&D Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Technology Acceleration Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Safety, Codes and Standards Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Fossil Energy Solid Oxide Fuel Cell Sub-Program	○	○	○	○	○	○	○	○	○	○	○

Comments:

5. The Hydrogen and Fuel Cells Program is funding high impact projects that have the potential to significantly advance the state of technology for the hydrogen and fuel cells industry? Please comment on the overall Hydrogen and Fuel Cells Program as well as each sub-program, as appropriate.

Please rate your response on a scale of 1 through 10 with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

	Strongly Disagree				Neutral				Strongly Agree		
	1	2	3	4	5	6	7	8	9	10	NA
Hydrogen and Fuel Cells Program Overall	○	○	○	○	○	○	○	○	○	○	○
Hydrogen Production and Delivery R&D Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Fuel Cell R&D Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Hydrogen Storage R&D Sub-Program	○	○	○	○	○	○	○	○	○	○	○

Technology Acceleration Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Safety, Codes and Standards Sub-Program	○	○	○	○	○	○	○	○	○	○	○
Fossil Energy Solid Oxide Fuel Cell Sub-Program	○	○	○	○	○	○	○	○	○	○	○

Comments:

6. In your opinion, what were the most significant accomplishments within the Hydrogen and Fuel Cells Program during the past year? Please consider the entire AMR content and entire DOE portfolio, including poster sessions, rather than the plenary talks alone.

Please respond for any program area as appropriate (Hydrogen Production, Delivery, Storage, Fuel Cells, Technology Acceleration, Systems Analysis, Safety, Codes and Standards, Solid Oxide, ARPA-E, Basic Science, etc.).

Please state areas requiring more attention or improvement. If you do not have a response, please select 'Not Applicable.'

☐ Not Applicable

7. The R&D supported by the overall Hydrogen and Fuel Cells Program is appropriate in light of private sector investments.

Please rate your response on a scale of 1 through 10 with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

Strongly Disagree				Neutral			Strongly Agree			
1	2	3	4	5	6	7	8	9	10	NA
○	○	○	○	○	○	○	○	○	○	○

Comments:

8. The R&D supported by the Solid Oxide Fuel Cell sub-program is appropriate in light of private sector investments.

Please rate your response on a scale of 1 through 10 with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

Strongly Disagree				Neutral			Strongly Agree			
1	2	3	4	5	6	7	8	9	10	NA
○	○	○	○	○	○	○	○	○	○	○

Comments:

9. Early Stage Research and Development: The Hydrogen and Fuel Cells Program is focused on early-stage R&D as aligned with Administration objectives for federal research funding. Please provide suggestions for early stage R&D that the Hydrogen and Fuel Cells Program should consider for promoting its goals and objectives.

10. Energy Materials Network (EMN) Consortia: Do you have any comments or recommendations on the Hydrogen and Fuel Cell Program's EMN consortia approach? Please state what is working effectively and areas that may benefit from further improvement. If you do not have a response, please select 'Not Applicable.'

☐ Not Applicable

11. H2@Scale: What are the strengths and weaknesses of the H2@Scale initiative? Do you have any recommendations for other H2@Scale research topics or recommendations to enable the scale up and value proposition of H2@Scale (e.g. a region with low electricity prices, excess curtailment, and hydrogen supply opportunity along with a co-located demand for hydrogen, etc.)? Please provide any other recommendations on H2@Scale. If you do not have a response, please select 'Not Applicable.'

☐ Not Applicable

12. Collaboration: The Hydrogen and Fuel Cells Program is collaborating with appropriate groups of stakeholders. Please add any additional comments particularly on which stakeholders (e.g. academia, companies, small businesses, types of industries, etc.) should be more engaged and in what manner.

Please rate your response on a scale of 1 through 10 with 1 indicating that you strongly disagree and 10 indicating that you strongly agree, or NA if you have no opinion. Please add any additional comments.

Strongly Disagree				Neutral				Strongly Agree		
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**NA**
○	○	○	○	○	○	○	○	○	○	○

Please also provide recommendations for how the Hydrogen and Fuel Cells Program can better coordinate R&D with other Offices in the Department of Energy (e.g., Office of Fossil Energy, Office of Nuclear Energy, Office of Science, ARPA-E, etc.), as well as with entities outside the Department of Energy (e.g. states, other agencies, industry, etc.).

13. International Collaboration: The Hydrogen and Fuel Cells Program collaborates through a number of international partnerships. For example, the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) is an international partnership to coordinate activities on hydrogen and fuel cells across 18 countries and the European Commission. The U.S. is assuming the chair role for IPHE in 2018. Please comment on actions DOE in conjunction with IPHE can undertake or activities that are effective/need improvement to accelerate progress in hydrogen and fuel cell technologies. If you do not have a response, please select 'Not Applicable.'

☐ Not Applicable

14. Prizes: Agencies have shown interest in implementing prizes and competitions as a mechanism to complement the conventional grant process. Examples include the H-Prize (H2Refuel) for a small-scale hydrogen fueling appliance that complements large retail stations. Please provide comments on the prize/competition approach and provide any suggestions for future prizes or competitions that would align with the goal of accelerating the widespread success of hydrogen and fuel cell technologies. If you do not have a response, please select 'Not Applicable.'

☐ Not Applicable

15. Please comment on the overall strengths and weakness of the Hydrogen and Fuel Cells Program and its portfolio of projects. Please provide strengths and weaknesses for each sub-Program as appropriate. In which technology areas should the Hydrogen and Fuel Cells Program put more or less focus on for future activities? If you do not have a response, please select 'Not Applicable.'

☐ Not Applicable

16. Do you have any other comments or suggestions to improve the overall effectiveness of the Hydrogen and Fuel Cells Program or any of its specific sub-programs? If you do not have a response, please select 'Not Applicable.'

☐ Not Applicable

List of Projects Presented but Not Reviewed

Project ID	Project Title	Principal Investigator Name	Organization
ARPAE01	Dual-Mode Energy Conversion and Storage Flow Battery	Chris Capuano	Proton OnSite
ARPAE02	Precious-Metal-Free Regenerative Hydrogen Electrode	Barr Zulevi	Pajarito Powder
ARPAE03	Low-Temperature NH_3 Cracking Membrane Reactor for Hydrogen Refueling Stations	Lin-Feng Li	Bettergy Corporation
ARPAE04	Protonic Ceramics for Energy Storage and Electricity Generation with Ammonia	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.
ARPAE05	Electricity from an Energy-Dense Carbon-Neutral Energy Carrier	Trent Molter	Sustainable Innovations
ARPAE06	Low-Cost Intermediate-Temperature Fuel-Flexible Protonic Ceramic Fuel Cell and Stack	Ryan O'Hayre	Colorado School of Mines
ARPAE07	High-Efficiency Ammonia Production from Water and Nitrogen	Hui Xu	Giner, Inc.
ARPAE08	High-Rate Ammonia Synthesis by Intermediate-Temperature Solid-State Alkaline Electrolyzer	Feng Zhao	Storagenergy Technologies, Inc.
ARPAE09	Direct Ammonia Fuel Cells for Transport Applications	Shimshon Gottesfeld	University of Delware
ARPAE10	Anion-Exchange Membrane Electrolyzers: The Low-Cost Alternative for Renewable Hydrogen Generation?	Rich Masel	Dioxide Materials
FC129	Advanced Catalysts and Membrane Electrode Assemblies for Reversible Alkaline Membrane Fuel Cells	Hui Xu	Giner, Inc.
FC177	Fiscal Year 2017 Small Business Innovation Research I Release 2: Over-Molded Plates for Reduced Cost and Mass of Polymer Electrolyte Membrane Fuel Cells	Daniel O'Connell	American Fuel Cell
FC178	Lab Call Fiscal Year 2018 (Membrane): Spirocyclic Anion Exchange Membranes for Improved Performance and Durability	Bryan Pivovar	National Renewable Energy Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
FC179	Lab Call Fiscal Year 2018 (Membrane): Stable Alkaline Membrane Based on Proazaphosphatranes Organic Super Base	Gao Liu	Lawrence Berkeley National Laboratory
FC180	Lab Call Fiscal Year 2018 (Membrane): High-Performing and Durable Pyrophosphate-Based Composite Membranes for Intermediate-Temperature Fuel Cells	Cortney Kreller	Los Alamos National Laboratory
FC181	Lab Call Fiscal Year 2018 (Reversible Fuel Cells): Microstructured Electrodes and Diffusion Layers for Enhanced Transport in Reversible Fuel Cells	Jacob Spendelow	Los Alamos National Laboratory
FC182	Lab Call Fiscal Year 2018 (Reversible Fuel Cells): Bipolar Membrane Development to Enable Regenerative Fuel Cells	Todd Deutsch	National Renewable Energy Laboratory
FC183	Lab Call Fiscal Year 2018 (Reversible Fuel Cells): Technology-Enabling Materials, Cell Design for Reversible Polymer Electrolyte Membrane Fuel Cells	Nem Danilovic	Lawrence Berkeley National Laboratory
FC184	New Fluorinated Ionomers for Enhanced Oxygen Transport in Fuel Cell Cathodes	Robert Lousenberg	Compact Membrane Systems
FC185	Novel Fluorinated Ionomer for Polymer Electrolyte Membrane Fuel Cells	Hui Xu	Giner, Inc.
FC186	New Approaches to Improved Polymer Electrolyte Membrane Fuel Cell Catalyst Layer	Earl Wagener	Tetramer Technologies, LLC
FC187	Development of Innovative Gas Diffusion Layers for Polymer Electrolyte Membrane Fuel Cells	Jason Morgan	AvCarb Material Solutions, LLC
FC188	High-Performance Gas Diffusion Layer	Minette Ocampo	pH Matter, LLC
FC189	Gas Diffusion Layer Media Development for Improved Polymer Electrolyte Membrane Fuel Cell Performance	Ashok Damle	Techverse, Inc.
FC190	Advanced Manufacturing of Gas Diffusion Layers with Highly Engineered Porosity	David Driscoll	Glacigen Materials, Inc.
FC191	Controlled Porosity and Surface Coatings for Advanced Gas Diffusion Layers	Christopher Lang	Physical Sciences Inc.

Project ID	Project Title	Principal Investigator Name	Organization
FC192	Nanostructured Carbon-Based Gas Diffusion Layers for Enhanced Fuel Cell Performance	Girish Srinivas	TDA Research, Inc.
FC193	Innovative Bilayer Microporous Layer for Polymer Electrolyte Membrane Fuel Cells	Chao Lei	Giner, Inc.
FE050-p	Development of Agile and Cost-Effective Routes for Manufacturing Reliable Ceramic Components for Solid Oxide Fuel Cell Systems	John Pietras	Saint-Gobain
FE051-p	Mapping of Temperature Profiles of Entire Solid Oxide Fuel Cells with 8 mm Spatial Resolution during 800°C Operations	Kevin P. Chen	University of Pittsburgh
FE052-p	Highly Active Hybrid Catalyst Impregnated Cathode for Proton-Conducting Solid Oxide Fuel Cells	Fanglin (Frank) Chen	University of South Carolina
FE053-p	High-Throughput, In-Line Coating Metrology Development for Solid Oxide Fuel Cell Manufacturing	Sean R. Bishop	Redox Power Systems, LLC
FE054-p	Highly Active and Contaminant-Tolerant Cathodes for Durable Solid Oxide Fuel Cells	Meilin Liu	Georgia Institute of Technology
FE055-p	On-Demand Designing of Cathode Internal Surface Architecture for Dramatic Enhancement of Solid Oxide Fuel Cell Performance and Durability	Xueyan Song	West Virginia University
FE056-p	Effect of Spinel Composition on the Electrical Conductivity and Coefficient of Thermal Expansion in the $(Ni,Co,Fe)_3O_4$ System	Jiahong Zhu	Tennessee Technological University
FE057-p	Operating Stresses and Their Effects on Degradation of Lanthanum–Strontium–Manganite (LSM)-Based Solid Oxide Fuel Cell Cathodes	Mark R. De Guire	Case Western Reserve University
FE058-p	Degradation and Performance Studies of Atomic-Layer-Deposition-Stabilized Nanocomposite Solid Oxide Fuel Cell Cathodes	Jason D. Nicholas	Michigan State University
FE059-p	Improving Nickel-Based Solid Oxide Fuel Cell Anode Resilience and Durability through Secondary Phase Formation	Robert A. Walker	Montana State University
FE060-p	Carbon-Tolerant Anode for Controlled Hydrocarbon Reformation in Solid Oxide Fuel Cells	Prabhakar Singh	University of Connecticut

Project ID	Project Title	Principal Investigator Name	Organization
FE061-p	Core–Shell Heterostructures as Solid Oxide Fuel Cell Electrodes	Srikanth Gopalan	Boston University
FE062-p	Improvement in Lifetime of Solid Oxide Fuel Cells, Utilizing Novel, In Situ Methods to Remove Cathodic Chromium Deposits	Uday B. Pal	Boston University
FE063-p	Cost-Effective Stabilization of Nanostructured Cathodes by Atomic Layer Deposition	Raymond J. Gorte	University of Pennsylvania
FE064-p	LG Fuel Cell Systems Solid Oxide Fuel Cell Prototype System Testing	Crispin DeBellis	LG Fuel Cell Systems, Inc.
FE065-p	High-Temperature Oxidation Behavior of 3D-Printed, Hot Isostatically Pressed, and Wrought AFA25 Alloys	Amit Pandey	LG Fuel Cell Systems, Inc.
FE066-p	Ultra-High-Temperature Anode Recycle Blower for Solid Oxide Fuel Cells	Hooshang Heshmat	Mohawk Innovative Technology, Inc
FE067-p	Pressurized Operation of a Planar Solid Oxide Fuel Cell Stack	Louis G. Carreiro	Naval Undersea Warfare Center Division Newport
FE068-p	Fluidized Bed Production of Surface Functionalized Powders for Solid Oxide Fuel Cell Cathodes	Nick M. Sbrockey	Structured Materials Industries, Inc.
FE069-p	Laser 3D Printing of Solid Oxide Fuel Cells	Jian Liu	PolarOnyx, Inc
FE070-p	Hybridization of Freeze Casting with Additive Manufacturing for Simplified Production of High-Performance Solid Oxide Fuel Cells	David R. Driscoll	Glacigen Materials, Inc.
FE071-p	Cold Spray Additive Manufacturing of Thermoelectric Generators	Harry B. Radousky	Lawrence Livermore National Laboratory
FE072-p	Flame-Powered Solid Oxide Fuel Cell Generators	Michael C. Tucker	Lawrence Berkeley National Laboratory
FE073-p	Progress in Metal-Supported Solid Oxide Fuel Cells	Emir Dogdibegovic	Lawrence Berkeley National Laboratory
FE074-p	Electrode Engineering Research and Development Progress at the National Energy Technology Laboratory	Gregory Hackett	National Energy Technology Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
FE075-p	Cell and Stack Degradation Evaluation and Modeling Progress at the National Energy Technology Laboratory	Gregory Hackett	National Energy Technology Laboratory
FE076-p	Advanced Reduced Order Model Prediction and Error Quantification Framework for Solid Oxide Fuel Cell Stacks	Brian Koeppel	Pacific Northwest National Laboratory
FE077-p	Optimal Operating Conditions for Performance and Reliability of Solid Oxide Fuel Cells	Kurtis P. Recknagle	Pacific Northwest National Laboratory
FE078-p	Small-Scale Test Platform for Solid Oxide Fuel Cell Stacks	Jeffry Stevenson	Pacific Northwest National Laboratory
FE079-p	Composite Approach to Tailoring Thermal Expansion of LSCo-based Ceramic Cathode Contact for Solid Oxide Fuel Cell Applications	Matt Chou	Pacific Northwest National Laboratory
FE080-p	Chromium Mitigation by Lanthanum–Strontium–Cobalt–Ferrite (LSCF)-Based Materials for Solid Oxide Fuel Cells	Matt Chou	Pacific Northwest National Laboratory
FE081-p	Long-Term Stability Tests of Low-Temperature and Standard Reactive Air Aluminization Process	Jung Pyung Choi	Pacific Northwest National Laboratory
FE082-p	Lanthanum–Strontium–Manganite (LSM)/ Yttria-Stabilized Zirconia (YSZ) Button Cell Tests in Cathode Air with Measured Chromium Concentrations	John S. Hardy	Pacific Northwest National Laboratory
FE083-p	Air Braze Optimization for Markets Targeted by Aegis Technology, Inc.	John S. Hardy	Pacific Northwest National Laboratory
FE084-p	Atomic-Layer-Deposition-Produced Interconnect Barriers for Improved Glass Seal Performance	Jeffrey F. Roeder	Sonata LLC
FE085-p	Surface Modification of Lanthanum–Strontium–Cobalt–Ferrite (LSCF) Cathode Powders by Atomic Layer Deposition	Jeffrey F. Roeder	Sonata LLC
FE086-p	Application of Computational Thermodynamics in Solid Oxide Fuel Cells	Yu (Michael) Zhong	Worcester Polytechnic Institute
FE1	Solid Oxide Fuel Cell Development Update at FuelCell Energy	Hossein Ghezel-Ayagh	FuelCell Energy, Inc.

Project ID	Project Title	Principal Investigator Name	Organization
FE10	Development and Understanding of Highly Active and Durable Oxygen Electrodes for Solid Oxide Fuel Cells	Xiao-Dong Zhou	University of Louisiana at Lafayette
FE11	Self-Regulating Surface Chemistry for More Robust Highly Durable Solid Oxide Fuel Cell Cathodes	Clement Nicollet	Massachusetts Institute of Technology
FE12	Scalable and Cost-Effective Barrier Layer Coating to Improve Performance and Stability of Solid Oxide Fuel Cell Cathode	Xingbo Liu	West Virginia University Research Corporation
FE13	Development of a Thermal-Spray, Redox-Stable Ceramic Anode for Metal-Supported Solid Oxide Fuel Cells	Richard Hart	General Electric Company
FE14	Metal-Supported Ceria Electrolyte-Based Solid Oxide Fuel Cell Stack for Scalable, Low-Cost, High-Efficiency, and Robust Stationary Power Systems	Charles Vesely and Bal Dosanjh	Cummins Power Generation/Ceres Power
FE15	Innovative, Versatile, and Cost-Effective Solid Oxide Fuel Cell Stack Concept	Nguyen Minh	University of California, San Diego
FE16	Intermediate-Temperature Solid Oxide Fuel Cells: Overview of Stack Size Scaling Efforts and Redox Robust All-Ceramic-Anode-Cell-Based Stacks	Sean Bishop and Bryan Blackburn	Redox Power Systems
FE17	Performance and Reliability Advancements in a Durable Low-Temperature Tubular Solid Oxide Fuel Cell	Praveen Cheeatamarla	Atrex Energy, Inc.
FE18	Mitigation of Chromium Impurity Effects and Degradation in Solid Oxide Fuel Cells: Role of Thermodynamics and Transport	Srikanth Gopalan	Boston University
FE19	Materials and Approaches for the Mitigation of Solid Oxide Fuel Cell Cathode Degradation in Solid Oxide Fuel Cell Power Systems	Prabhakar Singh	University of Connecticut
FE2	LG Fuel Cell Systems Solid Oxide Fuel Cell Power System Development	Cris DeBellis	LG Fuel Cell Systems, Inc.
FE20	Chromium Sensor for Monitoring Solid Oxide Fuel Cell Systems	Jeffrey Fergus	Auburn University
FE21	Highly Selective and Stable Multivariable Gas Sensors for Enhanced Robustness and Reliability of Solid Oxide Fuel Cell Operation	Radislav Potyrailo	General Electric Company

Project ID	Project Title	Principal Investigator Name	Organization
FE22	System Analysis of Fuel Cell Plant Configurations	Gregory Hackett	National Energy Technology Laboratory
FE23	Durable, Impermeable Solid Oxide Fuel Cell Brazes	Jason Nicholas	Michigan State University
FE24	Development of Chromium and Sulfur Getter for Solid Oxide Fuel Cell Systems	Prabhakar Singh	University of Connecticut
FE25	Effects of Composition and Operating Conditions on the Microstructure and Performance of Lanthanum–Strontium–Manganite (LSM)-Based Solid Oxide Fuel Cell Cathodes	Mark DeGuire	Case Western Reserve University
FE26	High-Temperature Anode Recycle Blower for Solid Oxide Fuel Cells	Jose Luis Cordova	Mohawk Innovative Technology, Inc.
FE27	Minimizing Chromium Evaporation from Balance-of-Plant Components by Utilizing Cost-Effective Alumina-Forming Austenitic Steels	Xingbo Liu	West Virginia University Research Corporation
FE3	National Energy Technology Laboratory Research and Development: Solid Oxide Fuel Cell Materials Development and Degradation Modeling	Gregory Hackett	National Energy Technology Laboratory
FE4	Solid Oxide Fuel Cell Development at Pacific Northwest National Laboratory: Overview	Jeff Stevenson	Pacific Northwest National Laboratory
FE5	Durability and Reliability of Materials and Components for Solid Oxide Fuel Cells	Edgar Lara-Curzio	Oak Ridge National Laboratory
FE6	Evaluation of Cathode Materials for Solid Oxide Fuel Cell Performance Reliability	Brian Ingram	Argonne National Laboratory
FE7	Degradation and Reliability Advancements in Tubular Solid Oxide Fuel Cells	Wensheng Wang	Atrex Energy, Inc.
FE8	Deposition of Nickel Nanoparticles in Solid Oxide Fuel Cell Anodes to Improve Performance	Soumendra N. Basu	Boston University
FE9	Scalable Nano-Scaffold Architecture on the Internal Surface of Solid Oxide Fuel Cell Anodes for Direct Hydrocarbon Utilization	Xueyan Song	West Virginia University Research Corporation

Project ID	Project Title	Principal Investigator Name	Organization
H2000	H2@Scale Overview	Bryan Pivovar and Mark Ruth	National Renewable Energy Laboratory
H2001	Scalable Electrolytic Systems for Renewable Hydrogen Production	Guido Bender	National Renewable Energy Laboratory
H2004	Tatsuno Coriolis Flow Meter Development Testing in High-Pressure Hydrogen	Rob Burgess	National Renewable Energy Laboratory
H2006	Membrance Electrode Assembly Manufacturing Automation Technology for the Electrochemical Compression of Hydrogen	Michael Ulsh	National Renewable Energy Laboratory
H2007	Megawatt-Scale Polymer-Electrolyte-Membrane-Based Electrolyzers for Renewable Energy System Applications	Kevin Harrison	National Renewable Energy Laboratory
H2011	Risk Analysis and Modeling to Improve Hydrogen Fuel Cell Vehicle Repair Garages	Chris LaFleur	Sandia National Laboratories
H2012	Evaluate High-Temperature Steam Electrolysis Coupled to Pressurized PWR/MCFR/TWR for Hydrogen Production and Energy Storage	Jamie Holladay	Pacific Northwest National Laboratory
H2013	Development, Validation, and Benchmarking of Quantitative Risk Assessment Tools for Hydrogen Refueling Stations	Chris LaFleur	Sandia National Laboratories
H2021	Hydrogen-Component Performance Diagnostic Testing	Danny Terlip	National Renewable Energy Laboratory
H2022	Develop a Tool to Estimate the Benefits of Tube-Trailer Consolidation Scheme for Station Builders	Amgad Algowainy	Argonne National Laboratory
H2025	Optimizing an Integrated Renewable-Electrolysis System	Josh Eichman	National Renewable Energy Laboratory
H2026	Hybrid Electrical/Thermal Hydrogen Production Process Integrated with a Molten Salt Reactor Nuclear Power Plant	Donald Anton	Savannah River National Laboratory
H2030	Hydrogen Materials Compatibility of Low-Cost, High-Pressure, Polymer Hydrogen Dispensing Hoses	Kevin Simmons	Pacific Northwest National Laboratory

Project ID	Project Title	Principal Investigator Name	Organization
H2035	Region-Specific Merchant Hydrogen Market Assessment and Techno-Economic Assessment of Electrolytic Hydrogen Generation	Richard Boardman	Idaho National Laboratory
H2036	Validating an Electrolysis System with High Output Pressure	Michael Peters	National Renewable Energy Laboratory
H2039	Turboexpander: Alternative Fueling Concept for Fuel Cell Electric Vehicle Fast Fill	Rob Burgess	National Renewable Energy Laboratory
H2041	California Hydrogen Infrastructure Research Consortium	Jennifer Kurtz	National Renewable Energy Laboratory
H2045	Methane Pyrolysis for Base-Grown Carbon Nanotubes and Carbon-Dioxide-Free Hydrogen over Transition-Metal Catalysts	Robert Dagle	Pacific Northwest National Laboratory
H2049	Valuation of Hydrogen Technology on the Electric Grid Using Production Cost Modeling	Josh Eichman	National Renewable Energy Laboratory
H2050	Holistic Fuel Cell Electric Vehicle/Hydrogen Station Optimization Model	Michael Peters	National Renewable Energy Laboratory
H2052	Merchant Hydrogen at Scale: A Technical-Economic Case Study of the Potential for Nuclear Hydrogen Production	Richard Boardman	Idaho National Laboratory
IA003	Hydrogen Fuel Cells for Powered Industrial Vehicles	Carroll Burgess	United States Postal Service
IA004	Fuel Cell Development for Tactical Vehicles	Kari Drotleff	United States Army Tank Automotive Research, Development and Engineering Center
IA005	Fuel Cell Unmanned Aerial Vehicle Development	Richard Stroman	Naval Research Laboratory
IA006	State- and Federal-Supported Hydrogen Research, Development, and Demonstration in Hawaii	Dave Molinaro	Hawaii Center For Advanced Transportation Technologies
IA007	Federal-Railroad-Administration-Sponsored Locomotive Project	Jack Brouwer	University of California, Irvine

Project ID	Project Title	Principal Investigator Name	Organization
IA008	National Fuel Cell Bus Program	Sean Ricketson	Federal Transit Administration
IA009	Fuel Cell Research and Development for Earth and Space Applications	Ian Jakupca	The National Aeronautics and Space Administration
IA010	The Brentwood Station Experience	Robin Nixon	National Park Service
IA011	Alternative Fuel Corridor Program	Diane Turchetta	Federal Highway Administration
IA012	Hydrogen-Related Activities at the United States Environmental Protection Agency	Susan Burke	United States Environmental Protection Agency
IA014	Basic Science Underpinning Hydrogen and Fuel Cells at the United States Department of Energy	Viviane Schwartz	United States Department of Energy Office of Basic Energy Sciences
IA015	National-Science-Foundation-Sponsored Hydrogen- and Fuel Cell-Related Research and Development	Carole Read	National Science Foundation
IA016	Neutron Imaging Study of the Water Transport in Operating Fuel Cells	David Jacobson	National Institute of Standards and Technology
IA017	Hydrogen from Wastewater Biogas	Nick Josefik	United States Army Corps of Engineers
IA018	Operational Energy from Seawater	Heather Willauer	United States Naval Research Laboratory
IA019	Designing a Fuel Cell Watercraft	Dana Wilkes	National Oceanic and Atmospheric Administration
IA020	The United States Department of Energy Advanced Manufacturing Office: What We Do	Kenneth Kort	United States Department of Energy Advanced Manufacturing Office
IA021	Chemical Catalysis for Bioenergy (ChemCatBio): Accelerating Research and Development in Catalytic Conversion of Biomass for Biofuels, Bioproducts, and Biopower	Nichole Fitzgerald and Robert Natelson	United States Department of Energy Bioenergy Technologies Office

Project ID	Project Title	Principal Investigator Name	Organization
IA022	Conversion of Methane to Hydrogen and Carbon via Catalytic Methane Decomposition	Ranjani Siriwardane	United States Department of Energy; National Energy Technology Laboratory
MN012	Integrated Regional Technical-Exchange Centers	Patrick Valente	Ohio Fuel Cells Coalition
MN013	Hydrogen Fuel Cell Nexus Business-to-Business Website	Alleyn Harned	Virginia Clean Cities at James Madison University
MN019	Material-Process-Performance Relationships in Polymer Electrolyte Membrane Catalyst Inks and Coated Layers	Michael Ulsh	National Renewable Energy Laboratory
PD038	Biomass to Hydrogen ($B2H_2$)	Pin-Ching Maness	National Renewable Energy Laboratory
PD102	Analysis of Advanced Hydrogen Production Pathways	Brian James	Strategic Analysis, Inc.
PD114	Flowing Particle Bed Solar-Thermal Oxidation-Reduction Reaction (RedOx) Process to Split Water	Alan Weimer	University of Colorado Boulder
PD116	Wide-Bandgap Chalcopyrite Photoelectrodes for Direct Solar Water Splitting	Nicolas Gaillard	University of Hawaii
PD125	Tandem Particle-Slurry Batch Reactors for Solar Water Splitting	Shane Ardo	University of California, Irvine
PD129	Novel Hybrid Microbial Electrochemical System for Efficient Hydrogen Generation from Biomass	Hong Liu	Oregon State University
PD170	Benchmarking Advanced Water-Splitting Technologies: Best Practices in Materials Characterization	Kathy Ayers	Proton OnSite
PD172	Low-Cost Magnetocaloric Materials Discovery	Robin Ihnfeldt	General Engineering and Research
PD173	Novel Membranes for Electrochemical Hydrogen Compression Enabling Increased Pressure Capability and Higher Pumping Efficiency	Zhefei Li	Xergy, Inc.

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PD174	Novel Sulfonated Block Copolymers for Efficient Electrochemical Hydrogen Compression	Trent Molter	Sustainable Innovations
SLAC	Reduced-Temperature Thermochemical Redox Reactions	William Chueh	SLAC National Accelerator Laboratory; Stanford University
ST014	Hydrogen Sorbent Measurement Qualification and Characterization	Phil Parilla	National Renewable Energy Laboratory
ST119	High-Capacity Hydrogen Storage Systems via Mechanochemistry	Vitalij Pecharsky	Ames Laboratory
ST120	Design and Synthesis of Materials with High Capacities for Hydrogen Physisorption	Brent Fultz	California Institute of Technology
ST134	Investigation of Solid-State Hydrides for Autonomous Fuel Cell Vehicles	Patrick Ward	Savannah River National Laboratory
ST135	HySCORE: Technical Activities at the National Institute of Standards and Technology	Thomas Gennett	National Renewable Energy Laboratory
ST136	HyMARC Seedling: "Graphene-Wrapped" Complex Hydrides as High-Capacity, Regenerable Hydrogen Storage Materials	Di Jia Liu	Argonne National Laboratory
ST137	HyMARC Seedling: Electrolyte-Assisted Hydrogen Storage Reactions	Channing Ahn	Liox Power, Inc.
ST140	Emergency Hydrogen Refueler for Individual Consumer Fuel Cell Vehicles	Michael Kimble	Skyhaven Systems, LLC
ST142	HyMARC Seedling: Fluorinated Covalent-Organic Frameworks: A Novel Pathway to Enhance Hydrogen Sorption and Control Isosteric Heats of Adsorption	Justin Johnson	National Renewable Energy Laboratory
ST143	HyMARC Seedling: Atomic Layer Deposition Synthesis of Novel Nanostructured Metal Borohydrides	Steven Christensen	National Renewable Energy Laboratory
ST144	HyMARC Seedling: Optimized Hydrogen Adsorbents via Machine Learning and Crystal Engineering	Don Siegel	University of Michigan

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ST145	HyMARC Seedling: Super-Metallated Frameworks as Hydrogen Sponges	Omar Yaghi	University of California, Berkeley
ST146	Precursor Processing Development for Low-Cost, High-Strength Carbon Fiber for Composite Overwrapped Pressure Vessel Applications	Matthew Weisenberger	University of Kentucky
ST147	Developing a New Polyolefin Precursor for Low-Cost, High-Strength Carbon Fiber	Mike Chung	Penn State University
ST148	Novel Plasticized Melt-Spinning Process of Polyacrylonitrile (PAN) Fibers Based on Task-Specific Ionic Liquids	Sheng Dai	Oak Ridge National Laboratory
ST149	General Techniques for Increasing Packing Density of Metal-Organic Frameworks for Enhanced Volumetric Storage of Hydrogen	William Morris	NuMat Technologies, Inc.
ST150	High Density Hydrogen Storage in Space-Filling Polyhedral Sorbents	Lawrence Dubois	NextGen Battery Technologies, LLC
ST151	Development of Novel Compaction Regimes for Hydrogen Storage Materials	Bryan Ennis	E&G Associates, Inc.