NATIONAL RENEWABLE ENERGY LABORATORY

H2@Scale Workshop Report

Proceedings from the H2@Scale Workshop
Golden, Colorado
November 16–17, 2016

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Office of Energy Efficiency & Renewable Energy
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Workshop Proceedings
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March 2017

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[1] Applied research and development (R&D) offices within the Office of Energy Efficiency and Renewable Energy (EERE)

List of Acronyms and Abbreviations

AEM	alkaline exchange membrane
AMO	Advanced Manufacturing Office
ARPA-E	Advanced Research Projects Agency-Energy
BETO	Bioenergy Technologies Office
CAISO	California Independent System Operator
CSP	concentrated solar power
DOE	U.S. Department of Energy
DRI	direct reduction of iron
EERE	Office of Energy Efficiency and Renewable Energy
EPSA	Office of Energy Policy and Systems Analysis
FCEV	fuel cell electric vehicle
FCTO	Fuel Cell Technologies Office
FE	Office of Fossil Energy
FIT	flash iron technology
GTO	Geothermal Technologies Office
H2	hydrogen
H2FIRST	Hydrogen Fueling Infrastructure Research and Station Technology
HyStEP	Hydrogen Station Equipment Performance
INL	Idaho National Laboratory
LCFS	Low Carbon Fuel Standard
NE	Office of Nuclear Energy
NREL	National Renewable Energy Laboratory
PEM	polymer electrolyte membrane
PGM	platinum group metal
R&D	research and development
RD&D	research, development, and demonstration
RFS	Renewable Fuel Standard
SETO	Solar Energy Technologies Office
SMR	steam methane reforming
SOEC	solid oxide electrolysis cells

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Executive Summary

The U.S. Department of Energy's (DOE's) National Renewable Energy Laboratory (NREL) hosted a technology workshop to identify the current barriers and research needs of the H2@Scale concept. H2@Scale is a concept regarding the potential for wide-scale impact of hydrogen produced from diverse domestic resources to enhance U.S. energy security and enable growth of innovative technologies and domestic industries. Led by DOE's Fuel Cell Technologies Office (FCTO), within the Office of Energy Efficiency and Renewable Energy (EERE), hydrogen and fuel cell activities have been coordinated across relevant DOE offices with research and development projects at multiple national laboratories, industry, and universities. NREL convened this workshop as part of its role in leading the multi-lab H2@Scale concept as well as the HydroGEN consortium, which focuses on early stage research, development, and innovation for low cost hydrogen production with multi-lab capabilities available for university and industry collaboration.[2] Feedback received from a diverse set of stakeholders at the workshop will guide the development of an H2@Scale roadmap for research, development, and early stage demonstration (RD&D) activities that can enable hydrogen as an energy carrier at a national scale.

Roughly 200 international stakeholders from industry, academia, and government agencies convened for a two-day program comprised of panel presentations and discussions along with targeted breakout sessions. A plenary session kicked off the event to provide an overview and background information regarding the H2@Scale initiative and introduce specific topics to be discussed during the workshop. Topics covered in the subsequent panel presentations included:

1. **Collaboration across DOE offices**: Representatives from 10 offices within DOE discussed current and future opportunities for hydrogen within their technology portfolios.
2. **Hydrogen production technologies and infrastructure**: Representatives from industry described the current status and research and development (R&D) challenges associated with large-scale electrolysis and hydrogen delivery technologies, such as pipelines, caverns, liquefaction, and fueling stations.
3. **Electricity grid and utilities**: Representatives from electric utilities discussed the compatibility of hydrogen production with current and future electricity generation technologies, such as high-temperature nuclear generation, solar power, and wind power.
4. **Industrial end uses**: Presenters discussed the current and value-add uses of hydrogen in growing industries, such as chemicals production, fuels production, and metals refining.

Between the two days, breakout sessions were conducted around six different areas of H2@Scale. These sessions discussed priority technological, economic, and policy needs to enable the H2@Scale vision, along with the roles of government, industry, and academia in addressing these challenges. A brief summary of the major takeaways from each breakout session are below:

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[2] HydroGEN was launched by FCTO, and is composed of NREL, Lawrence Berkeley National Laboratory, Sandia National Laboratories, Idaho National Laboratory, Lawrence Livermore National Laboratory, and Savannah River National Laboratory. Their website is available here: https://www.h2awsm.org/.

1. Hydrogen production
    a. Reductions in the cost of hydrogen should be achieved through production at/near the point of use, standardization, and use of near-term feedstock (such as off-gases from chlor-alkali plants).
    b. Manufacturing technologies are necessary to enable reductions in electrolyzer cost at large scales.
    c. Validation of the performance and costs of large-scale electrolyzer integration with the grid and value-add applications is necessary.
    d. Regulatory structures should be developed to monetize the many benefits of electrolyzers, including their ability to provide grid services.
    e. Education and advocacy regarding the merits of hydrogen production from water is necessary for both the general public and regulators.
    f. Progress measures for H2@Scale were defined, with respect to hydrogen production technologies, market penetration and support of hydrogen, and regulatory framework for hydrogen production and use.
2. Value-add applications
    a. Key markets that could be early adopters of electrolyzers must be identified and pursued. These markets could include applications that leverage both hydrogen and the oxygen produced as a by-product of electrolysis, or markets where use of hydrogen is a value-add, such as stationary power.
    b. Blending of hydrogen in the natural gas infrastructure requires R&D on the compatibility of end users with hydrogen.
    c. The merits of hydrogen must be clearly communicated to the general public.
3. Infrastructure needs
    a. Creation of a national pipeline network was identified as the desired long term end goal.
    b. Large scale compressor technology will require significant R&D efforts to achieve desired durability and cost metrics.
    c. Mechanisms for hydrogen delivery should be standardized (e.g., capacities, interfaces) to leverage economies of scale.
    d. A skilled workforce for hydrogen infrastructure must be developed.
    e. Large geological storage sites will need to be developed as hydrogen demand increases.
    f. A timeline was proposed for H2@Scale infrastructure priorities in the near and long term.

4. Chemicals production
    a. Small-scale onsite hydrogen production systems may have a value proposition over delivered hydrogen in specialty chemicals industries. The threshold at which onsite production is advantageous over delivered hydrogen must be established.
    b. Co-locating chemical production plants near hydrogen production facilities has a value proposition by lowering the cost of infrastructure.
    c. Fundamental R&D (e.g., catalyst development) is needed to lower the costs of chemical synthesis.
    d. Bench-scale demonstrations of electrolyzer integrations should be conducted to address commercialization risks.
    e. Price of electrolytic hydrogen will be a barrier to adoption.
5. Fuels production
    a. Demonstrations of large-scale electrolyzers are necessary to prove the viability of their integration into value-add applications.
    b. Electrolyzer companies should engage in sustainability indices that investors use to incorporate sustainability into their portfolios.
    c. Techno-economic analysis should be conducted to account for the potential for customers to benefit from by-products of hydrogen production, such as oxygen from electrolysis and carbon from steam methane reforming (SMR).
    d. Potential advocates for electrolytic hydrogen should be engaged, such as industrial gas companies, states with Renewable Portfolio Standards, and regions of the country with curtailment issues.
    a. Price of electrolytic hydrogen must achieve parity with SMR-based hydrogen.
6. Metals refining
    a. Direct reduction of iron (DRI) is an established steelmaking process that could use both hydrogen and oxygen from electrolysis. Expansion of this process requires an evaluation of its business case, along with additional R&D.
    b. There may be smaller markets that currently use delivered hydrogen which may benefit from onsite electrolysis.
    c. A pilot scale demonstration of flash iron technology (FIT) and DRI should be conducted.
    d. Price of electrolytic hydrogen must decline for it to have a viable business case.

Overall, a diverse group of stakeholders provided valuable input on the opportunities, barriers, and path forward to achieve the H2@Scale vision. DOE is currently funding a techno-economic analysis project to assess the value proposition of H2@Scale and devising an RD&D roadmap based on the feedback and discussions from the workshop.

Introduction

H2@Scale addresses the potential of wide-scale hydrogen production and utilization in the United States to enable growth in diverse domestic industries and address key issues such as resiliency, domestic competitiveness, and creation of American jobs in emerging multibillion dollar markets.

While hydrogen is used widely in mature industries today (such as oil refining and ammonia production), most hydrogen in the United States is produced by SMR. Another approach to hydrogen production is electrolysis, wherein electricity is used to split water into hydrogen and oxygen. Electrolyzers are used widely in applications where natural gas is not available, SMR is not economical (e.g., submarines, laboratories, power plants in remote areas),[3] or purity is a significant concern. At megawatt scales (>1,000 kg H_2/day), an additional advantage of electrolyzers over SMR is that they can be used as a form of "demand response" on the grid, supplying marketable grid services.[4] Megawatt-scale electrolyzers can also be hybridized with existing sources of baseload power, such as nuclear plants, to produce hydrogen when the plants would otherwise be curtailed.[5] This approach would create a value stream that improves the economics of these assets, many of which are fully amortized and operational but may otherwise be retired. Finally, electrolyzer manufacturing is a market that the United States currently leads, with significant exports overseas for the grid stability, power plant, and industrial gas markets. Sustained investments in electrolyzers will ensure that the United States retains this lead over existing competition from countries in Asia and Europe.

Due to their ability to respond to fluctuations in power supply within subseconds, electrolyzers can increase their power draw from the grid to produce hydrogen when power supply on the grid is in excess.[6] Conversely, when power supply on the grid is less than demand, electrolyzers can be turned down. Given their flexibility, electrolyzers can participate in several wholesale electricity markets, including "regulation up and down", "spinning reserves and non-spinning reserves", and "grid frequency modulation".[7,8,9] In the past few years, electrolyzers have been

[3] K. Ayers, "Commercial Electrolysis: Setting the Stage for H2@Scale" (presented at the H2@Scale Workshop, Golden, CO, November 16-17, 2016), https://energy.gov/sites/prod/files/2016/12/f34/fcto_h2atscale_workshop_ayers.pdf.

[4] "Flexible and Distributed Energy Resources," Technology Assessment 3D in *Quadrennial Technology Review 2015* (Washington, DC: U.S. Department of Energy, 2015), https://energy.gov/sites/prod/files/2015/09/f26/QTR2015-3D-Flexible-and-Distributed-Energy_0.pdf.

[5] "Hybrid Nuclear-Renewable Energy Systems," Technology Assessment 4K in *Quadrennial Technology Review 2015* (Washington, DC: U.S. Department of Energy, 2015), https://energy.gov/sites/prod/files/2016/06/f32/QTR2015-4K-Hybrid-Nuclear-Renewable-Energy-Systems.pdf.

[6] R. Hovsapian, "Dynamic Modeling and Validation of Electrolyzers in Real Time Grid Simulation" (presented at the 2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review, Washington, DC, June 6-10, 2016), https://www.hydrogen.energy.gov/pdfs/review16/tv031_hovsapian_2016_o.pdf.

[7] J. Eichman, K. Harrison, and M. Peters, *Novel Electrolyzer Applications: Providing More than Just Hydrogen* (Golden, CO: NREL, 2014), NREL/TP-5400-61758, http://www.nrel.gov/docs/fy14osti/61758.pdf.

[8] J. Eichman, A. Townsend, and M. Melaina, *Economic Assessment of Hydrogen Technologies Participating in California Electricity Markets* (Golden, CO: NREL, 2016), NREL/TP-5400-65856, http://www.nrel.gov/docs/fy16osti/65856.pdf.

[9] J. Eichman and F. Flores-Espino, *California Power-to-Gas and Power-to Hydrogen Near-Term Business Case Evaluation* (Golden, CO: NREL, 2016), NREL/TP-5400-67384, http://www.nrel.gov/docs/fy17osti/67384.pdf.

demonstrated in such demand response applications in Germany[10] and the United States.[11] Moreover, R&D is being conducted on integration of electrolyzers with electricity generation and heat from nuclear power plants (i.e., "hybrid energy systems") to improve their economics when the nuclear plants would otherwise be curtailed.[12]

The H2@Scale concept is based in the synergistic potential of hydrogen production and hydrogen utilization in industry to achieve national economic and sustainability goals in a manner that is greater than the sum of their parts. The H2@Scale vision is depicted in Figure 1.

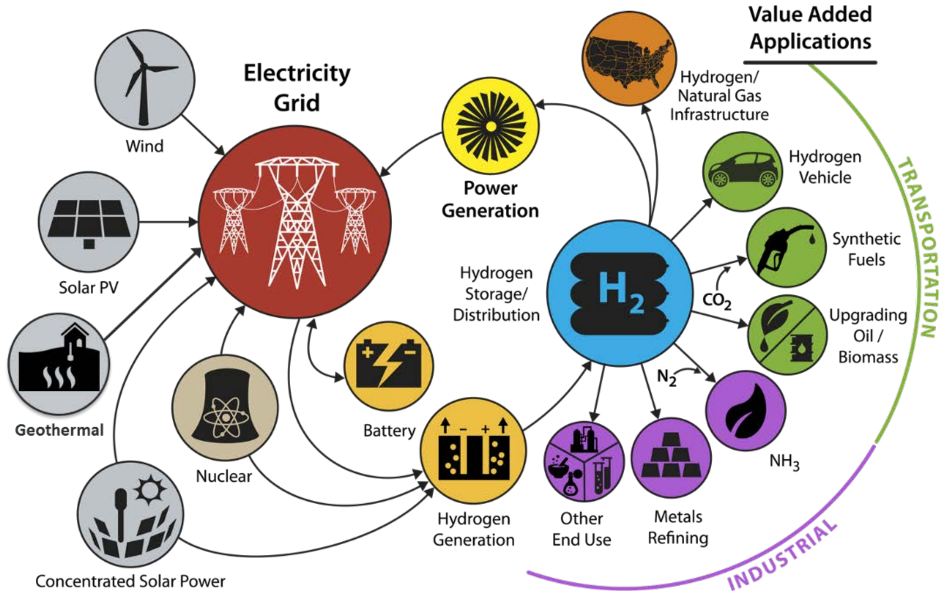

Figure 1. H2@Scale schematic

An H2@Scale energy system offers broad potential benefits, which include:

1. Providing flexibility across sectors such as transportation, industrial and stationary power applications.
2. Enhancing the stability of the power grid through grid services, demand response, and energy storage.
3. Improving the economics of thermal energy generation sources (e.g., nuclear, geothermal), many of which are already amortized but are otherwise being decommissioned, by hybridizing them with hydrogen production technologies
4. Enabling a leadership role in global hydrogen and fuel cell markets.

[10] Siemens, "Green light for green hydrogen at Energiepark Mainz," news release, July 2, 2015, http://www.siemens.com/press/pool/de/feature/2014/corporate/2014-05-energiepark-mainz/pr2015070276pden.pdf.
[11] University of California, Irvine, "In a national first, UCI injects renewable hydrogen into campus power supply," news release, December 6, 2016, https://news.uci.edu/faculty/in-a-national-first-uci-injects-renewable-hydrogen-into-campus-power-supply/.
[12] M. Ruth et al., "Nuclear-renewable hybrid energy systems: Opportunities, interconnections, and needs," *Energy Conversion and Management* 78 (2014): 684-94, http://dx.doi.org/10.1016/j.enconman.2013.11.030.

5. Enabling growth in U.S. industries, such as oil refining and chemicals production.
6. Enhancing domestic energy security by increasing our use of domestic resources, including fuels.
7. Addressing human health issues through reductions in emissions, and environmental issues such as water and resource consumption.

The U.S. electricity grid will require mechanisms to enable stability as it is revolutionized by the deployment of inexpensive solar and wind generation. From 2008 to 2015, the cost of land-based wind energy declined by 41%, and the cost of utility-scale photovoltaic installations declined by 64%.[13] The price reductions in wind energy have already made it cost-competitive with combined cycle natural gas plants in certain parts of the country, even without incentives.[14] Concurrently with these cost reductions, wind and solar power increased to more than two-thirds of the newly added U.S. generating capacity in 2015 and accounted for 5.3% of that year's total electricity generation.[15] However, this increase in power generation from intermittent sources necessitates improvements in grid flexibility to buffer differences between electrical power supply and demand. The lack of flexibility on the grid is already causing curtailment of electricity in several states,[16] and it is projected to increase in the coming years.[17] Low wholesale prices for electricity brought on by the inflexibility of wind and solar energy have also resulted in nuclear plant closures on economic grounds.[18] Deploying grid-tied electrolyzers is a promising means to increase grid flexibility by providing dispatchable demand capacity.

Multiple researchers have identified electrolyzers as being advantageous over conventional mechanisms of energy storage when seasonal scales are necessary. At relatively low penetrations of inflexible generation, grid stability can be achieved through a variety of means, such as installing more transmission lines, installing natural gas power plants whose output can be modulated rapidly and within a wide power range, using short-time-scale energy storage (e.g., pumped hydro and batteries), and deploying smart appliances and other technologies capable of automated demand response.[19] However, studies have shown that when renewable generation exceeds a certain percentage of the grid's total energy use (e.g., roughly 50%), large seasonal mismatches in electricity demand and production arise.[17,19] Because the energy storage capacity and power demand of common energy storage mechanisms are proportional (e.g., in lithium-ion, sodium sulfur, and lead acid batteries), it becomes very expensive to store seasonal

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[13] "Revolution Now 2016," fact sheet (Washington, DC: U.S. Department of Energy, 2016), https://www.energy.gov/eere/downloads/revolutionnow-2016-update.
[14] EIA, "Levelized Cost and Levelized Avoided Cost of New Generation Resources in the Annual Energy Outlook 2016" (Washington, DC: U.S. Energy Information Administration, 2016), http://www.eia.gov/outlooks/aeo/pdf/electricity_generation.pdf.
[15] "Frequently Asked Questions: What is U.S. electricity generation by energy source?" U.S. Energy Information Administration, last updated April 1, 2016, https://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3.
[16] L. Bird, J. Cochran, and X. Wang, *Wind and Solar Energy Curtailment: Experience and Practices in the United States* (Golden, CO: NREL, 2014), http://www.nrel.gov/docs/fy14osti/60983.pdf.
[17] N. Schlag et al., *Western Interconnection Flexibility Assessment* (San Francisco: Energy & Environmental Economics, Inc., 2015), http://www.ethree.com/wp-content/uploads/2017/02/WECC_Flexibility_Assessment_Report_2016-01-11.pdf.
[18] M. Mobilia, "Fort Calhoun becomes fifth U.S. nuclear plant to retire in past five years," *Today in Energy*, U.S. Energy Information Administration, October 31, 2016, http://www.eia.gov/todayinenergy/detail.php?id=28572.
[19] P. Denholm and M. Hand, "Grid Flexibility and Storage Required to Achieve Very High Penetration of Variable Renewable Electricity," *Energy Policy* 39 (2011): 1817-30.

overgeneration in these devices.[19] Electrolyzers provide the ability to store energy seasonally because the power demand of an electrolyzer can be decoupled from the amount of stored chemical energy by increasing the capacity of hydrogen gas storage infrastructure. Indeed, the large storage capacity of, for example, the natural gas infrastructure[20] can be leveraged to store hydrogen[21] or, potentially, synthetic methane produced from hydrogen and carbon dioxide.[22]

While the initial capital cost of electrolyzer deployments on the grid will be significant, their use can reduce overall energy system costs. Deploying seasonal storage reduces the marginal curtailment of solar and wind generation, thereby reducing the life cycle cost of electricity from these sources.[19] Similarly, electrolyzers can be integrated with nuclear power plants to improve their economics. Electricity and process heat from nuclear power can be used to produce hydrogen at times of low power demand, such that these baseload plants are able to operate at relatively stable output throughout the year (instead of being turned down). Electrolyzer integration is compatible with both existing[23] and next generation nuclear plants.[24,25] The ability of electrolyzers to provide the lowest system cost for a sustainable electricity, transportation, and natural gas sector has been shown in Williams et al. Moreover, many stable U.S. industries, such as oil refining, chemicals production, and fuel cell electric vehicles (FCEVs), will require increased domestic hydrogen production for their own growth in the coming decades.[26] Thus, enabling the production of hydrogen through electrochemical or thermochemical means using domestic energy feedstocks represents a critical tool in enabling sustainable domestic energy security and industrial growth.

The potential benefits of hydrogen within the energy system aren't new. The term 'Hydrogen Economy' was termed in the 1970s, focused largely on hydrogen's potential to displace petroleum from transportation applications. In the mid 2000s, President George W. Bush introduced the Hydrogen Fuel Initiative "to develop hydrogen-powered fuel cells, hydrogen infrastructure and advanced automotive technologies." The subsequent R&D investments from both government and industry have led to game-changing accomplishments in recent years. Costs of electrolyzers have fallen by 80% since 2000, three models of FCEVs have been made commercially available in the United States since 2015, over 1,000 FCEVs are currently registered in the United States, and 25 hydrogen fueling stations are now publicly open for retail

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[20] "Natural Gas: About U.S. Natural Gas Pipelines," U.S. Energy Information Administration, https://www.eia.gov/pub/oil_gas/natural_gas/analysis_publications/ngpipeline/index.html.

[21] M. Melaina, M. Penev, and J. Zuboy, "Hydrogen Blending in Natural Gas Pipelines," *Handbook of Clean Energy Systems* (2015): 1-13, http://dx.doi.org/10.1002/9781118991978.hces205.

[22] J. Williams et al., *Pathways to Deep Decarbonization in the United States*, the U.S. report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations (San Francisco: Energy and Environmental Economics, Inc., 2014), revision with technical supplement, Nov. 16, 2015.

[23] *Feasibility Study of Hydrogen Production at Existing Nuclear Power Plants* (Idaho Falls: INL, 2009), INL/EXT-09-16326, https://avt.inl.gov/sites/default/files/pdf/hydrogen/HydoProdFeasibilityStudyNucPwrPlantsJuly09Combined.pdf.

[24] *Nuclear-Integrated Hydrogen Production Analysis* (Idaho Falls: INL, 2010), TEV-693 Revision 1, https://art.inl.gov/NGNP/INL Documents/Year 2010/Nuclear-Integrated Hydrogen Production Analysis rev 1.pdf.

[25] L. Brown et al., High Efficiency Generation of Hydrogen Fuels Using Nuclear Power: Final Technical Report for the Period August 1, 1999 through September 30, 2002 (San Diego: General Atomics, 2003), https://doi.org/10.2172/821587.

[26] R. Boardman, "H2 Utilization" (presented at the H2@Scale Workshop, Golden, CO, November 16-17, 2016), https://energy.gov/sites/prod/files/2016/12/f34/fcto_h2atscale_workshop_boardman_2.pdf.

sale of hydrogen.[27] An additional 25 stations are currently funded and under development in California, with 100 planned[27] and 12 stations are planned for deployment with no government funding in the Northeast.[28] In addition, auto manufacturers recently announced planned investments of about $90 million for U.S. manufacturing of FCEVs.[29] These achievements are a testament to the revolutionary improvements possible in technologies for hydrogen production, delivery, and use with government and industry investments aligned toward specific goals. The purpose of the H2@Scale workshop was to identify specific goals that industry and government can address collaboratively to remove technological, policy, and market barriers to wide-scale deployment of low-cost hydrogen to serve the power grid and existing U.S. industries.

The appendices to this report provide background on key technical aspects of H2@Scale, for the interested reader.

[27] J. Baronas et al., Joint Agency Staff Report on Assembly Bill 8: 2016 Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California (Sacramento: California Energy Commission, 2017), CEC-600-2017-002, http://www.energy.ca.gov/2017publications/CEC-600-2017-002/CEC-600-2017-002.pdf.
[28] Air Liquide, "Air Liquide announces locations of several hydrogen fueling stations in northeast U.S.A.," press release, April 7, 2016, https://www.airliquide.com/united-states-america/air-liquide-announces-locations-several-hydrogen-fueling-stations-northeast.
[29] B. Snavely, "GM, Honda to make hydrogen fuel cells at Michigan factory," *USA Today*, January 30, 2017, http://www.usatoday.com/story/money/cars/2017/01/30/general-motors-honda-fuel-cell-deal/97240096/.

Summary of Presentations

Plenary Session

Bill Tumas *(Associate Lab Director, NREL)*, welcomed everyone to the workshop and reviewed safety procedures at NREL.

The following overview presentations were then provided by DOE, NREL, Southern California Gas Company (SoCalGas), and Idaho National Laboratory (INL).

1. **Reuben Sarkar** (*Deputy Assistant Secretary for Transportation, DOE's Office of Energy Efficiency and Renewable Energy [EERE]*) provided an overview of EERE's high-level clean energy goals, aligned with the goals of the United Nations Conference of Parties 21 as well as the global Mission Innovation Initiative.[30] He also encouraged the audience to review the Revolution Now report,[31] which highlights recent strides in the costs and performance of renewable generation in the United States. Mr. Sarkar subsequently discussed key recent successes in the hydrogen and fuel cell industry, including:
    - The commercial launch of FCEVs in the United States for the first time in history in 2015.
    - Global revenue of $2 billion in the fuel cell market in 2014.[32]
    - 30% year-on-year growth of global fuel cell shipments since 2010.[33]
    - Launch of the H2USA public-private partnership in 2013, which has now reached over 50 members.
    - Development and deployment of the Hydrogen Station Equipment Performance (HyStEP) device in 2016, as a part of the Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) project. HyStEP expedites the process of fueling station commissioning from months to weeks.

    Mr. Sarkar emphasized that hydrogen production can leverage clean and renewable sources of power (e.g., wind, solar, and nuclear), and can thereby reduce emissions from a host of end uses in the transportation and industrial sectors. He identified H2@Scale as one of the biggest, boldest initiatives to be proposed at the annual National Laboratories Big Idea Summit, and he concluded by reiterating the importance of collaborative research between government and industry to further lower costs of hydrogen and fuel cells.
2. **Dr. Sunita Satyapal** (*Director of DOE's EERE's Fuel Cell Technologies Office [FCTO]*) provided information on the current status of hydrogen production and delivery

[30] "Mission Innovation," Mission Innovation, 2016, http://mission-innovation.net/.
[31] "Revolution Now," U.S. Department of Energy, 2016, https://www.energy.gov/revolution-now.
[32] "Fuel Cells," in *Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan* (Washington, DC: U.S. Department of Energy, 2016), section 3.4, https://energy.gov/sites/prod/files/2016/10/f33/fcto_myrdd_fuel_cells.pdf.
[33] S. Satyapal, "U.S. Department of Energy Hydrogen and Fuel Cells Program" (joint plenary presentation at the 2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Washington, DC, 2016), https://www.hydrogen.energy.gov/pdfs/review16/02_satyapal_plenary_2016_amr.pdf.

in the United States and showed that meeting FCTO's targets for hydrogen and FCEVs could reduce U.S. petroleum use in the transportation sector dramatically.[34] Dr. Satyapal then discussed the diverse sources of power generation necessary to achieve these targets, showing back-of-the-envelope calculations on the amount of hydrogen the United States would need for wide-scale deployment of FCEVs along with the amount of power necessary to produce the hydrogen.

Dr. Satyapal summarized the relevant research projects that FCTO is currently funding to define and characterize the impact of H2@Scale. In the fall of 2017, FCTO awarded an analysis project to forecast the expected supply and demand of hydrogen from clean and renewable sources under various assumptions of future electricity prices, forecast infrastructure requirements of wide-scale deployment of clean hydrogen, and assess the impact of H2@Scale on domestic resources (e.g., water) and pollution. Dr. Satyapal then presented a project currently being conducted by NREL and INL to demonstrate and validate the performance of an electrolyzer that is dynamically integrated with a simulated electricity grid, such that it produces hydrogen during optimal time-of-use rates. Subsequently, she discussed the Request for Information that FCTO issued on H2@Scale in September 2017. Key themes in responses to the Request for Information included interest in:

- Innovative hydrogen production technologies
- Integrated hydrogen systems
- Innovation in hydrogen storage and delivery technologies
- Use of hydrogen to enable grid stability and energy storage
- Data collection and sharing on the value proposition and feasibility of H2@Scale
- Deployments of hydrogen in near-term markets, including buses, ammonia, and steel.

Dr. Satyapal concluded by stating that the overall goal of this cross-sector workshop is to drive development of an H2@Scale Roadmap, which will include RD&D needs of hydrogen production from diverse domestic sources, use of hydrogen for grid stability and energy storage, development of industrial-scale hydrogen delivery and storage infrastructure, and penetration of clean/sustainable (including renewable) hydrogen in current and future end-use markets.

3. **Dr. Bryan Pivovar** (*Manager of Electrochemical Engineering and Materials Chemistry Group at NREL, and National Laboratory Lead for H2@Scale*) provided an in-depth overview of the H2@Scale concept. He began by acknowledging the many different stakeholders across the national laboratory system, government, and industry that have been involved in creating the H2@Scale concept. Dr. Pivovar then framed H2@Scale in the context of sustainability, explaining that a systems-level solution across the transportation, industrial, and power generation sectors is necessary for a meaningful reduction in pollution within the United States.

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[34] "Well-to-Wheels Greenhouse Gas Emissions and Petroleum Use for Mid-Size Light-Duty Vehicles" (Washington, DC: Offices of Bioenergy Technologies, Fuel Cell Technologies, and Vehicle Technologies, 2013), Program Record 13005 (revision #1), https://www.hydrogen.energy.gov/pdfs/13005_well_to_wheels_ghg_oil_ldvs.pdf.

Dr. Pivovar explained that the contract prices of wind power and solar power have fallen dramatically since 2009, which has resulted in exponential growth in deployments. One of the remaining challenges with deployments of renewable power is their intermittency, which leads to curtailment of power during times of the day when generation exceeds demand. Since curtailment reduces the value proposition of renewables, there is a growing need for grid technologies that can buffer the mismatch between supply and demand. Dr. Pivovar described hydrogen production as a viable solution to this challenge. Electrolyzers produce hydrogen from water using electricity and are able to moderate their output rapidly as a function of energy input. Electrolyzers therefore have potential to be integrated with the electricity grid as a source of variable demand that can produce hydrogen when power supply exceeds demand. During such times of overgeneration, the price of power is relatively low, such that hydrogen can be produced at lower cost than otherwise achievable. The hydrogen produced can then be sold into many current industries, such as oil refining, ammonia production, or FCEVs.

By enabling higher penetrations of renewable power, electrolyzers can dramatically reduce U.S. energy consumption, as renewable generators (e.g., wind and solar) consume less energy to operate than thermal generation. Moreover, replacement of conventional hydrogen (produced from SMR) with renewably produced hydrogen would dramatically reduce U.S. emissions. Dr. Pivovar presented Sankey diagrams that the national laboratories had created to quantify these reductions. For example if the proportion of U.S. energy consumption that is achieved from renewables reaches 30%, the expected reduction in U.S. energy requirements is expected to be about 25%. Dr. Pivovar closed with a discussion of the cross-cutting R&D advances necessary in low- and high-temperature electrolysis, hydrogen storage and distribution, and hydrogen end uses to enable H2@Scale.

4. **Dr. Jeffrey Reed** *(Director of Business Strategy and Advanced Technology, SoCal Gas)* presented on electrolysis integration with energy infrastructure. SoCal Gas is interested in this concept largely due to federal policy requiring reductions in ozone in California and state policy targeting an 80% reduction in greenhouse gas emissions by 2050. Moreover, California is already experiencing the need for grid services, such as flexible loads, to manage the mismatch between the supply and demand of renewables throughout any given day (i.e., the "duck curve"). Dr. Reed highlighted "power-to-gas" as a critical solution to all of these challenges. The "power-to-gas" concept involves dynamically connecting an electrolyzer to the grid, such that it produces hydrogen when the price of power is low due to oversupply. The hydrogen produced can then be delivered directly to end users or reacted with carbon dioxide to form methane. The methane can then be delivered through the natural gas infrastructure to end users (e.g., industrial heating). Dr. Reed described techno-economic analysis on power-to-gas that the University of California, Irvine is completing in collaboration with NREL to characterize the scenarios in which power-to-gas has a value proposition. He explained that, while power-to-gas is a grid service with the ability to regulate voltage and mitigate the duck curve, special rates are not yet in place to incentivize the technology. Deployment of power-to-gas will require developments in the market for grid services, along with reductions in electrolyzer cost, improvements in electrolyzer efficiency, and a willingness of customers to pay a premium for renewable fuel. Dr. Reed concluded by announcing that the

California Hydrogen Business Council is interested in supporting this concept, and California is looking to have hydrogen significantly involved in its fuel mix by 2030.

5. **Dr. Richard Boardman** (*Energy Systems Integration Initiatives at INL, and National Laboratory co-Lead for H2@Scale*) discussed the tremendous potential of electrolytic hydrogen in many industrial processes. Key points from Dr. Boardman's analyses included:

    - Steelmaking via DRI and electric arc furnaces is growing commercially. These processes have the advantages of lower capital cost and lower feedstock cost than conventional blast arc furnaces. DRI currently relies on mixtures of hydrogen and carbon monoxide gas for reduction of iron ore. Replacement of this mixture with pure hydrogen could dramatically reduce emissions from steelmaking.
    - Producing methanol via co-electrolysis of carbon dioxide and steam, rather than the conventional approach, can reduce emissions from the methanol industry. Co-electrolysis would create a new market for carbon dioxide while replacing the industry's dependence on methane.
    - The primary use for fuels in manufacturing is for process heat. Replacement of conventional fuels that are combusted for heating (e.g., natural gas) with hydrogen would deeply reduce emissions from the manufacturing sector.
    - Supplying refineries with hydrogen from electrolyzers rather than SMR would reduce U.S. refinery greenhouse gas emissions by 25%.
    - Using hydrogen in refinery boilers and heaters in lieu of natural gas combustion would reduce U.S. refinery greenhouse gas emissions by 20%.

    Dr. Boardman then discussed the costs of electrolysis in comparison to SMR. He showed that hydrogen production from electrolyzers becomes cost competitive as the price of electricity falls. The costs of electrolysis can be further reduced by leveraging waste heat in industry (e.g., high-temperature nuclear power plants), in a process known as high-temperature steam electrolysis. Dr. Boardman's conclusions were that that the demand for hydrogen in a host of industries is strong, but growth in clean production of hydrogen from solar, wind, and/or nuclear generation is necessary.

DOE Collaboration Panel

During this panel, representatives from eight different DOE offices were asked to describe the relevance of H2@Scale to their mission and to share their opinions on gaps in the vision and technology areas that an H2@Scale roadmap should address. This panel was moderated by Reuben Sarkar, the Deputy Assistant Secretary for Transportation at EERE.

1. **Geothermal Technologies Office (GTO)**, Holly Thomas (*Technology Manager of Mineral Recovery*) highlighted the current abundance and future growth potential of geothermal power in the United States. She explained that the United States is currently the world leader in geothermal power production and that most geothermal power is produced from naturally occurring hydrothermal reservoirs. These reservoirs naturally contain high-temperature heat, permeable rock, and fluid. High-temperature fluid from

hydrothermal reservoirs is extracted and used to produce geothermal power. GTO also funds research on the creation of manmade reservoirs in regions of the country that have high-temperature heat but lack porous rock with fluid. An emerging use for geothermal fluid is to recover minerals from the fluid. Mineral recovery would clean the fluid, lowering the risk of damage to a geothermal power plant, while also creating a value stream if the minerals are sold. Ms. Thomas explained that hydrogen gas recovery from geothermal steam may be a viable approach to hydrogen production. She also identified integration with conventional geothermal power plants and/or hybrid geothermal systems as an approach to clean hydrogen production. Hybrid systems integrate geothermal fluid with heat sinks, such that they can additionally be used for cooling applications. Ms. Thomas concluded by saying that techno-economic analysis is crucial for H2@Scale to move forward.

2. **Bioenergy Technologies Office (BETO)**, Kevin Craig (*Program Manager of Conversion Technologies*) highlighted that BETO's goal is to produce liquid fuels that integrate directly with existing infrastructure and that can replace petroleum in *all* of its applications (including gasoline, diesel, jet fuel, heavy distillates, chemicals, and other products). Mr. Craig explained that upgrading of bio-oils into biofuels requires hydrogen to remove oxygen in the oils. Affordable hydrogen is therefore key to bio-oil refining, and it is a key aspect of BETO's multi-year plans. Research areas of interest include hydrogen production from the aqueous phase of bio-oil, upgrading of biomass, and anaerobic digestion of biogas (e.g., from landfills). Mr. Craig believes that integrating technologies from a systems perspective is important for H2@Scale, as well as identifying value-add applications for hydrogen.

3. **Solar Energy Technologies Office (SETO)**, Dr. Levi Irwin (*Technology Development Manager*) focused on the enormous potential of hydrogen as a form of storing energy from concentrated solar power (CSP). Energy storage mechanisms typically considered for CSP systems include sensible storage, latent/phase change materials, and thermochemical systems. He also described a recent project at Pacific Northwest National Laboratory, wherein an innovative thermochemical system was developed that reforms methane into syngas (a mixture of carbon monoxide and hydrogen) using sunlight from CSP. The syngas produced can then be used in lieu of natural gas at power plants. Power plants using this system require about 20% less natural gas feedstock than otherwise necessary, which lowers their environmental impact. Dr. Irwin also identified metal hydrides as a viable approach to thermochemical storage. Systems with multiple metal hydride beds can use heat from CSP plants to store hydrogen. Shuttling hydrogen between the beds by leveraging pressure gradients will absorb and release heat. Integrating CSP with metal hydride beds thereby creates a flexible system that can store and generate heat as necessary throughout the day and night. Dr. Irwin stated that for H2@Scale to be viable, the scalability of hydrogen storage should be a focus, and expert techno-economic analysis is necessary to establish the value proposition of the concept.

4. **Advanced Manufacturing Office (AMO)**, Dr. Sridhar Seetharam (*Senior Technical Advisor*) discussed AMO's priorities, which include making technologies to produce clean energy, and increasing the amount of clean energy used in manufacturing processes. AMO is currently funding research on the development of catalysts to improve the efficiency of conventional hydrogen production processes (e.g., steam reforming),

and the development of membranes for efficient separation/recovery of hydrogen from gaseous mixtures. In terms of increasing clean energy in manufacturing, Dr. Seetharam explained that AMO is focused on improving the efficiency of metals refining. Hydrogen gas and tri-gen fuel cell systems can be leveraged in improving the efficiency of metals refining. AMO is interested in integrating hydrogen into both of their priorities. Dr. Seetharam pointed out that materials research (e.g., on hydrogen pipelines) will be necessary for H2@Scale.

5. **Office of Fossil Energy (FE)**, David Lyons (*Technology Manager*) discussed FE's Advanced Energy Systems Program, which is focused on energy conversion through heat engines and advanced turbines. Mr. Lyons described FE's research on advanced turbines that operate on syngas and allow for pre-combustion pollution control that is more effective than conventional post-combustion designs. He also identified solid oxide fuel cells as enabling efficient power conversion at utility scales. Mr. Lyons highlighted the potential of gasification technologies to produce syngas from a host of feedstock. The syngas can then be used in diverse applications, such as chemicals production, or fed to separation technologies that allow for recovery of both hydrogen and carbon dioxide. Mr. Lyons closed with a discussion of chemical looping projects around the world. Chemical looping is an innovative combustion technology being funded by FE that relies on obtaining oxygen from chemical carriers rather than air. The use of carriers (e.g., a metal oxide) rather than air as the source of oxygen allows the combustion gas to be composed of high concentrations of carbon dioxide, steam, and hydrogen. The high concentrations of these gases enable easier separation of each gas, such that each gas can be recovered for use in valuable applications. Mr. Lyons pointed out that H2@Scale should focus on robust, low-risk technologies that leverage hydrogen, such as production of liquid fuels and use of waste streams for hydrogen production.
6. **Office of Nuclear Energy (NE)**, Carl Sink (*Program Manager for Advanced Reactor Deployment*) shared NE's vision of the future. NE envisions integration of process heat from high-temperature nuclear reactors with electrolyzers and thermochemical systems (e.g., the sulfur iodine cycle) to enable hydrogen production from nuclear plants. He explained that NE believes that future nuclear power generation will use lightwater small modular reactors and high-temperature gas cooled reactors instead of conventional lightwater reactors. High-temperature gas cooled reactors will generate significant process heat that could be leveraged for high-volume hydrogen production. Additionally, NE is interested in the integration of nuclear power with renewables to enable a flexible "hybrid energy system". While nuclear baseload complements intermittent renewable generation well, nuclear plants should be leveraged for other purposes when the grid does not require them; idling nuclear power plants is inefficient and uneconomical. One approach to prevent idling would to be use the thermal heat or electric power from nuclear plants to produce commodities (e.g., fuels) when the plants are not needed by the grid. NE is contributing to H2@Scale through dynamic cross-lab modeling of how grids operate. Furthermore, NE can assist with stakeholder engagement, international coordination, regional case studies, and market analysis.
7. **Office of Energy Efficiency and Renewable Energy (EERE)**, Kevin Lynn (*Director of Grid Integration*) explained that EERE's Grid Integration Initiative's goal is to integrate diverse power generation sources into a reliable, affordable, sustainable, and resilient

system. As part of the Grid Integration Initiative, EERE is developing a platform of tools and technologies to enable development and management of a new operating grid system, accounting for system services, visibility, controls, and security. The potential of hydrogen in storage of renewable energy, ancillary grid services and demand response via electrolyzers, and energy generation via dispatchable fuel cells is very exciting. The main challenges to these opportunities will be determining the best role for hydrogen to play in a grid system and characterizing the costs of hydrogen in these applications.

8. **Office of Energy Policy and Systems Analysis (EPSA)**, Sarah Garman (*Policy Analyst*) pointed out that EPSA does not fund technology development directly but that they analyze strategies for emissions reduction. She commented that it is critical to think about policies that will enable H2@Scale implementation in various technologies and sectors.

Discussion with Audience

1. *When hydrogen is produced from waste heat, can oxygen produced as a by-product be useful?*

   Both Nuclear Energy and Solar Energy participants agreed that there is potential, since oxygen is important for combustion processes. However, gas separation is expensive.

2. *Has anyone calculated how much renewable energy we must generate to produce wide-scale renewable hydrogen and meet clean fuel requirements?*

   FCTO is funding that analysis now to determine the resources that are necessary now and in the future. The analysis will not rely only on one resource to produce the hydrogen, as hydrogen can be produced from diverse domestic resources.

3. *The H2@Scale Roadmap must include storage, compression, and delivery of hydrogen, and must work to minimize losses of hydrogen in these stages.*

   The Solar Energy participant agreed that managing a gas can be costly. SETO is eager to understand optimal ways to store hydrogen.

4. *These technologies have been around for quite a while. What is the main goal of H2@Scale – is it to take advantage from existing technologies and optimize them, or discovery and innovation?*

   Panelists agreed that H2@Scale incorporates systems integration, as well as development and demonstration of new technologies, such as novel forms of energy storage and materials R&D. DOE representatives explained that that FCTO recently launched two national lab consortia to conduct research on low technology readiness level technologies for hydrogen production and fuel cells. Both of these consortia, HydroGEN and ElectroCat, are aligned with H2@Scale.

5. *Since hydrogen storage does not qualify for storage procurement mandates, how will it be cost competitive with lithium ion batteries and other storage technologies?*

   Panelists pointed out that diverse forms of energy storage will be necessary in the future, and that it is important to focus on the advantages that each mechanism delivers. They identified the need for educating regulatory stakeholders on the potential of hydrogen energy storage, especially since the technology is relatively new. It was also mentioned that the California Hydrogen Business Council is working to engage with the California Public Utilities Commission to get hydrogen included in the regulatory framework.

6. *Comment shared that there are adversaries, particularly in the political/policymaking process, who are against hydrogen in pipelines, for storage, etc. Beyond education, we need to show that it is a viable energy storage technology.*
7. *Direct water splitting is necessary to avoid the efficiency losses associated with conventional renewable electrolysis. This is missing from the H2@Scale vision.*

   DOE panelists pointed out the direct water splitting R&D is being funded as part of the HydroGEN consortium FCTO recently launched. In fact, NREL recently set a world record for conversion efficiencies via photoelectrochemical water splitting. The H2@Scale vision does not exclude hydrogen production via means other than electrolysis.

Hydrogen Production, Storage, and Distribution Panel

Presentations described the current status and R&D challenges associated with large-scale electrolysis and hydrogen delivery technologies, such as pipelines, caverns, liquefaction, and fueling stations.

1. **Dr. Kathy Ayers** (*Vice President of Research and Development, Proton Onsite*) reviewed the history of polymer electrolyte membrane (PEM) electrolysis. She explained that electrolyzers' early applications were for oxygen production in closed environments, such as outer space or underwater, which has driven certain legacy design elements. Over the past 20 years, electrolyzers have scaled from the watt to megawatt scale. New platforms have been developed to enable use of electrolyzers in diverse applications, including lab instrumentation, weather balloons, small chemical processes, power plants, and, recently, energy storage. Costs have declined as electrolyzers have scaled, but manufacturing innovations are still necessary. The electrolyzer growth curve sheds some insight on projections for H2@Scale—any new hydrogen production technology will likely take about 20 years to reach megawatt scales. Accordingly, gigawatt (GW)-scale hydrogen production from renewable sources in the near-term will require conventional electrolysis. Dr. Ayers identified key areas of electrolyzers with potential for cost reduction, including:

   - Manufacturing technologies and advanced materials for membrane electrode assemblies
   - Costs of bipolar plates
   - Costs of catalysts.

   Dr. Ayers pointed out that industry investments have been focused on scale-up of electrolyzer technology rather than on implementation of fundamental R&D advancements in electrolyzer costs.

   Dr. Ayers explained that Proton only releases new electrolysis platforms after identifying new markets and characterizing their value proposition. She reviewed several recent examples of new platforms, including megawatt-scale electrolyzers being deployed in Europe. Dr. Ayers highlighted a project in Germany wherein an electrolyzer is being used to produce hydrogen that is subsequently combined with carbon dioxide from biogas to produce biomethane. Dr. Ayers concluded with a discussion of opportunities and challenges. Advancements in electrolysis require fundamental R&D in electrolyzer materials and components, improvements in electronics to integrate electrolyzers with power supplies, and the development of manufacturing processes. A commercial challenge in electrolysis is the time lag between proof-of-concept of a new technology to commercialization. With respect to the energy storage market, electrolyzer companies require additional clarity on:

- How electrolyzers are expected to interact with the grid
- Optimal sizes of electrolyzers for grid integration
- "Typical" use profiles for electrolyzers and cost models
- Regulatory framework for electrolyzers used for energy storage.

2. **Al Burgunder** (*Praxair*) presented on the current status of centralized hydrogen production and delivery. Mr. Burgunder explained that conventional SMR is compatible with many hydrocarbon sources, including natural gas, biogas, and refinery off-gases. He also highlighted opportunities for hydrogen recovery from waste streams of existing chemical production processes, such as ethane cracking and chlor-alkali production. Mr. Burgunder stressed such processes are already producing hydrogen streams that will be wasted if not recovered. He further explained that, while industrial gas companies are willing to purchase hydrogen from renewable sources, their decisions are based primarily on the cost and reliability of the hydrogen. Mr. Burgunder concluded with a review of commercial modes of hydrogen delivery, including compressed gas trailers, liquid tankers, and high-pressure pipelines.
3. **Tim Brown** (*First Element*) reviewed the status of First Element's hydrogen fueling stations in California. As the country's largest fueling station developer, First Element has built 15 stations that are currently commercially open and has funding to build four more. However, the California Air Resources Board's projections for growth in the FCEV market indicate that the state may face a shortfall of hydrogen by 2022. The amount of spare capacity within existing hydrogen production plants must be quantified, and an expansion of production plants may be necessary. Moreover, California will likely need large hydrogen fueling stations by 2020 to match FCEV demand. H2@Scale is necessary to support the light duty vehicle market, and ways to integrate hydrogen production for FCEVs with hydrogen production for other industries is critical.

Questions from Audience

1. *Do you know of interest from industry to pay a premium for green hydrogen? Is there a scheme supported by DOE for certification of green hydrogen?*

   To pay a premium for green hydrogen, industry would require incentives and an accounting system that does not exist today.

2. *What is the difference in efficiency for liquid vs. gaseous hydrogen?*

The benefit of liquid is that the liquefaction plants can scale up their output, and liquid tankers carry significantly more hydrogen than gaseous tube trailers. The most efficient form of hydrogen delivery is via pipelines, but they require a strong business case to justify the significant capital investment.

3. *Comment: There is an opportunity for the electrolysis industry. There is a clear need for hydrogen and more sources of hydrogen (hopefully green). PEM electrolysis is ready to scale and economics can work—the time is now, but the industry needs regulatory support and funding to drive scale in these areas. It is also worth mentioning that electrolyzers are a U.S. technology manufactured domestically.*

4. *How does solid oxide electrolysis fit in to your vision?*

   Solid oxide is a technology we should be exploring, but it is far behind low-temperature electrolysis technologies. We need to study synergies between solid oxide electrolysis and other technologies.

5. *What can you tell us about hydrogen station reliability in California?*

   Reliability was very poor when stations were first being rolled out. However, First Element's uptime is currently at about 98%. They still have stations down about one day/month, but are working on improving.

6. *What is your perspective on hydrogen carriers (e.g., organic liquid carriers) to transport hydrogen at high density?*

   Panelists explained that they are focused on the near-term market, and are unaware of any carriers being commercially deployed today. If they were reliable and cost-effective today, they would be used.

   Panelists also explained that the commodity industry has razor thin margins, because of which carriers are not currently being considered. They may be used in the future to carry large volumes of hydrogen long distances.

7. *If the company could reduce one cost for storing and transporting hydrogen, what would it be?*

   Panelists commented that the cost of labor associated with reliability issues is a significant cost. Compressors are the largest capital cost, in terms of station parts.

   They also commented that an increase in the U.S. Department of Transportation's 80,000-lb. weight limit for vehicles would allow for higher-capacity tube trailers and tankers, and thereby significantly lower the cost of delivery. At the fueling station, technologies are needed to effectively use liquid hydrogen rather than gas.

8. *In terms of hydrogen production, what variables help companies make a decision on what type of hydrogen to use?*

   Panelists explained that, while they value renewable hydrogen, their first priority is to sell hydrogen at a price that is near parity with gasoline. If hydrogen from SMR is significantly cheaper than hydrogen from renewable sources, they will use the former.

9. *Are there economics that could enable distributed generation at stations, such that the stations would be scalable in capacity and/or multiple stations could be supplied by nearby generation rather than requiring large deliveries?*

   Electrolysis is a good option for distributed production since it can moderate its output to match demand. However, its capital costs and time-of-use charges make it uneconomical. On-site SMR is challenging because SMR units operate best at constant load, but demand for hydrogen at a station changes diurnally. The biggest issue with onsite generation is space constraints at existing gasoline stations.

10. *How long will it take, how many stations are needed to see the advantages to get to liquid hydrogen?*

    Liquid hydrogen is almost viable at the small volumes of hydrogen stations today. The primary challenge with using liquid hydrogen is the fire codes, which make use of liquid hydrogen at gasoline stations very challenging. The economics of liquid hydrogen are not the challenge.

Grid and Utilities Panel

This panel consisted of presentations regarding the compatibility of hydrogen production with current and future electricity generation technologies.

1. **Mr. Michael Pesin** (*Deputy Assistant Secretary, Advanced Grid Research and Development at DOE*) discussed the changing electrical grid and need for energy storage. Grid modernization must happen due to a changing generation mix, growing demands for more resilient and reliable grid, and growing supply- and demand-side opportunities for customers to participate in electricity systems. Energy storage can address many different aspects of grid modernization outlined above and is often considered the “holy grail”. For DOE, the key characteristics of a modernized grid are that it is reliable, resilient, secure, affordable, flexible, and sustainable. Hydrogen shows potential for being used in demand-side storage. However, the technology requires a market and policy to be developed and deployed.

2. **Dr. Noah Meeks** (*Southern Company*) presented the perspective of a vertically-integrated utility located primarily in the south. Southern Company has made strong investments in wind and solar power to date and expects growth in wind power in 2017 and beyond; they are targeting owning 3 GW of wind power and at least 10 GW of solar power in the Southeast by 2030. This growth in renewables will create different energy storage needs throughout the country. Projects financed with investment tax credits will incentivize storage of solar energy, while those receiving production tax credits will incentivize storage of thermal energy. Hydrogen energy storage is advantageous over conventional technologies (e.g., pumped hydro or batteries) because of its scalability and flexibility; hydrogen can be stored and reused locally or sold to other markets. Within transportation, a potential advantage of FCEVs is their mass energy density.

   Dr. Meeks also pointed out that, in order to derive the environmental benefits of hydrogen, the hydrogen must be produced by electrolysis using clean sources of electricity. Nuclear power is a clean, scalable, low-cost source of power today with a strong value proposition in the Southeast, where solar and wind resources are less than other parts of the country. Dr. Meeks discussed high-temperature nuclear reactors as the future of nuclear generation and pointed out that Southern Company is already working on the development of a molten salt reactor. High-temperature nuclear reactors will be compatible with hydrogen production from water, via processes that are currently at low technology readiness levels today, such as solar thermochemical water splitting. They are also interested in the development of liquid hydrogen carriers to allow transmission of hydrogen at high energy densities. Dr. Meeks closed with a few examples of industry-led demonstrations that Southern Company would be interested in partaking in, including hydrogen production via electrolysis in the Southeast and integration of hydrogen production via the hybrid sulfur thermochemical cycle with nuclear generation.

3. **Marino Monardi** (*PG&E Corporation*) presented on the interest PG&E has in hydrogen. PG&E's interest in hydrogen is driven by three factors. First, hydrogen can be used as a clean fuel to help meet California's greenhouse gas emissions reduction goals. Second, hydrogen can be produced from both gas and electricity—products the utility provides; hydrogen is produced primarily via SMR (using natural gas) today, and production via electrolysis (using electricity) is expected in the future. Third, hydrogen can provide services to the electric grid, including energy storage and grid balancing. The increase in renewables in California has contributed to relatively low wholesale power prices during periods with significant renewable generation. The availability of low-cost wholesale power supports economical electrolyzer-based hydrogen production. However, the availability of low cost power will be influenced by many key variables, including: expansion of the California Independent System Operator (CAISO) grid, investments in electric storage, growth in renewables penetration, retirements of baseload generation, and growth in demand. Additionally, the accessibility of wholesale power to power-to-gas technologies must be established. The Federal Energy Regulatory Commission had to rule that battery storage could access wholesale power pricing for charging. Such regulatory modifications will be necessary for power-to-gas to be economically viable as well. Other challenges utilities will face will include ensuring the safety of the concept, ensuring affordability considering the capital investments that would be necessary, and satisfying other stakeholder objectives.

4. **Ryan Jones** (*Evolved Energy Research*) described strategies identified by the Deep Decarbonization Pathways Project to achieve deep decarbonization in the United States while retaining economic growth and lifestyles similar to those today. The project team identified three pillars that are necessary for deep decarbonization: 1) improvements in end-use energy efficiencies, 2) decarbonization of electricity, and 3) increase in the share of energy supplied by electricity and electrically derived fuels. Hydrogen has a strong value proposition in decarbonization strategies. First of all, hydrogen production and power-to-gas systems are the lowest cost, long duration balancing solutions available to electricity systems with inflexible supply. Additionally, hydrogen fuels are more compatible with certain end uses than electrification or battery storage (e.g., long haul trucking). Moreover, hydrogen already has significant industrial applications. Of the strategies identified for deep decarbonization, significant growth in nuclear power (i.e., the "high nuclear" case) is the most compatible with steady growth in hydrogen production from electrolysis. High penetrations of nuclear power will not require long-term storage to buffer electricity imbalances as much as high penetrations of renewables would. As a result, a "high nuclear" scenario will be able to rely on production of fuels,

such as hydrogen, for balancing. In very high renewable scenarios, on the other hand, it is advantageous to methanate hydrogen produced with electrolysis to produce methane, which is easier to store for long periods and can utilize existing gas pipelines. The form of hydrogen production that will be preferred in the future (e.g., low-temperature electrolysis, high-temperature electrolysis, SMR, or partial oxidation of hydrocarbons) will depend on the composition and balancing needs of the grid.

Mr. Jones provided several high-level insights into the H2@Scale concept. He mentioned that the net cost of a future energy system should be the parameter that analyses plan toward, rather than the levelized cost of hydrogen. Additionally, large-scale electrolyzers in the future will not be able to rely exclusively on renewable overgeneration and near zero market prices for hydrogen production. Electrolyzers providing grid balancing in future scenarios will also likely operate at low capacity factors. Accordingly, lowering their capital cost is more important than improving their efficiency for future grid applications. In the context of grid services, electrolyzers are expected to have a large enough impact on electricity markets that they will be pricemakers. Thermal power plants without carbon capture will, however, need to operate at low capacity factors to provide capacity to the energy system. Stationary fuel cells will have to compete economically in providing capacity, not energy, to gain market share. Mr. Jones concluded by emphasizing that it will reduce the overall cost of a decarbonized electricity sector to anticipate long-duration balancing challenges early and to deploy solutions, such as grid electrolysis, that will be effective in solving both long-duration balancing and shorter time-scale problems, which will be experienced first.

5. **Angelina Galiteva** (*California Independent System Operator*, *CAISO*) discussed CAISO's perspective on the future of the power grid. There are many trends transforming the U.S. electricity sector, including falling prices of renewables, increases in the penetrations of natural gas and renewable power on the grid, and increases in distributed generation and bidirectional power flows. Renewable energy represented 65% of new generation capacity deployed by the United States in 2015. Additionally, the Clean Energy and Pollution Reduction Act of 2015 has established aggressive goals for California, including 1) increasing use of renewable energy in California to 50% by 2030, 2) doubling energy efficiencies of electricity and natural gas end uses by 2030, 3) increasing investments in transportation electrification, and 4) transforming CAISO into a regional organization, with approval from legislature. Ms. Galiteva explained that the role of CAISO is to manage and operate the grid in California and implement state policy. Imbalance on the grid (i.e., "duck curve") and curtailment of power is currently a challenge in regions of the country with significant intermittent generation. A successful approach to manage this imbalance has been the launch of the Energy Imbalance Market. The Energy Imbalance Market dynamically identifies the lowest cost energy supply for a given customer's demand from across grid operating regions in the Western United States. This approach helps buffer imbalances between supply and demand across operating regions that were previously relatively siloed. Since its inception in 2014, the Energy Imbalance Market has saved three different independent system operators a total of about $114M.

   Closer integration of more regional power grids is expected to be a viable approach to grid reliability.

Ms. Galiteva subsequently discussed how hydrogen could be a player in the future grid. Electrolysis is already being integrated into wholesale markets in Europe, and CAISO is supportive of hydrogen in the United States. Use of electrolysis to produce hydrogen that is then used to generate synthetic gases (e.g., methane) or liquid fuels would decarbonize existing industries while leveraging existing delivery infrastructure. Hydrogen and stationary fuel cells also have potential for energy storage applications. U.S. deployments of stationary fuel cells have been steadily growing since 2003.

Ms. Galiteva closed with several highlights of the largest renewable projects in the world, many of which are located in California. She pointed out that the state is moving toward electrification of as many end uses as possible, from transportation to space heating, and that clean energy companies are also growing rapidly. As an example, Tesla has reached a market value of $34 billion in just 12 years. Ms. Galiteva concluded by highlighting that on the regulatory side, the hydrogen industry must get more involved and be more vocal and visible. As of now the industry does not lobby, participate, or ask for regulations. Regulators and industry can work together to build a path toward H2@Scale.

Questions from Audience

1. *There are policies that moved solar power forward in California. Do you have any ideas on potential regulatory structures to propel H2@Scale forward in California?*

   Panelists agreed that policy is definitely necessary, and an incentive program could help. The independent system operators need to hear from the hydrogen industry on what they should focus on to incentivize and regulate. She also commented that hydrogen missed inclusion in the Low Carbon Fuel Standard (LCFS), which could have incentivized renewable hydrogen production.

   Panelists pointed out that transportation is a key starting point for H2@Scale. PG&E is looking to have a role in building out fueling stations in the future but is unsure how to engage in that space right now. Policy mandates, like the Renewable Portfolio Standards, will be necessary to incentivize use of hydrogen.

2. *Are you aware of any modeling on renewable natural gas?*

   Such analysis is being conducted in Europe, and Germany, in particular, has a number of power-to-gas projects. *Note that DOE also has projects on producing natural gas from hydrogen and carbon dioxide, and preliminary modeling/analysis would be included.*

3. *Do you have experience integrating hydrogen into natural gas pipeline?*

   This has been discussed by PG&E and others. Pipeline integrity is a concern, as well as determination of the concentrations of hydrogen that can be safely injected in pipelines. Research is necessary to address these concerns.

Industrial End-Uses Panel

1. This panel was kicked off with a presentation from **Dr. Mark Johnson** (*Director of DOE's EERE's Advanced Manufacturing Office*). Dr. Johnson provided an overview of AMO, highlighting that the nexus of energy technologies and manufacturing benefits the economy, energy security, and the environment, a triple bottom line. AMO's goals are to

develop a robust U.S. energy systems economy where products are developed and manufactured in the United States, and to make the entire U.S. manufacturing sector more productive. AMO focuses include development of energy efficiency technologies, platforms for manufacturing of clean energy technologies, partnerships across industries and government, and talent in manufacturing. AMO funds research to identify the potential improvements in energy efficiency in key industries, such as chemicals and petroleum refining. The chemical industry uses a lot of hydrogen, particularly in the production of ammonia. For renewable hydrogen production, we should target the price point that commercial processes currently pay.

2. **Dr. Brian Walker** (*EERE's Strategic Programs Office*) described several studies that the Office is conducting on identifying the largest sources of emissions in the United States, users of industrial heat, and potential sources of low-emission heat. Any deep energy transformation will have to incorporate industrial needs (in addition to transportation, residential, and commercial needs). Strategic Programs is currently funding several studies to define the potential of systems that integrate renewable generation, nuclear generation, and energy storage to reduce U.S. emissions, enhance grid stability, and supply heat to industrial consumers while meeting the nation's energy demand.

   Dr. Walker concluded with a discussion on the importance of electrolysis to achieve cost parity with SMR to penetrate any market wherein the price of hydrogen is more important than the ancillary benefits that electrolyzers provide (e.g., hydrogen purity and cyclability). He recommended that the H2@Scale concept focus on value-add applications wherein use of electrolysis or hydrogen in general can provide performance advantages that incumbent technologies do not have; examples would include the ability of FCEVs to fuel in 3–5 minutes or stationary fuel cells to provide hours of backup power. Other successful EERE technologies have followed this path of identifying and developing minimum viable products that can launch them into brand new markets with growth potential. Dr. Walker concluded that the DOE will continue to conduct techno-economic analysis to ensure that our roadmaps are innovative and realistic.

3. **Jon La Follet** (*New Energy Technologist, Shell*) presented on the supply chain and infrastructure needs for wide scale hydrogen deployment. To achieve the required reduction in carbon emissions from the mobility sector, a mix of powertrains will be needed, including FCEVs, battery electric vehicles, and biofuels. Energy short markets will persist in the future (even when accounting for local renewable resources), and intercontinental hydrogen supply chains will therefore be needed to bridge the demand. Shell is looking at liquid hydrogen as an option for supply of decarbonized energy into mobility, along with other sectors of use. However, many technological challenges must be addressed for the viability of this concept, including:
   - Scale-up and cost reduction of hydrogen liquefaction.
   - Development of cargo containment systems with low boil-off, for use in liquid tankers.
   - Health, safety, and environment management of large-scale liquid hydrogen supply chains.
   - Development of regulations and standards for liquid hydrogen supply chains.

- Development of new hydrogen demand sectors (e.g., hydrogen for power, residential, and industrial heat).

4. **Dr. Grigorii Soloveichik** (*Program Director, DOE Advanced Research Projects Agency-Energy [ARPA-E]*) started by providing an overview of DOE's ARPA-E. ARPA-E funds high-risk R&D with potential to bring transformative technologies to market. He then discussed ammonia as an energy vector and hydrogen carrier. Ammonia has a wide range of uses today, including agriculture and chemicals, and even has potential in combustion engines. Benefits of ammonia as an energy carrier include its energy density, safety, and low rates of boil-off/loss, all of which make it cost-competitive relative to transmission of electricity or delivery of hydrogen. Ammonia can also be used directly in fuel cells, achieving performance comparable to mixtures of hydrogen and nitrogen gas, or dehydrogenated to release hydrogen. Dr. Soloveichik then discussed methods of producing ammonia. The conventional approach, Haber-Bosch synthesis, requires nitrogen (typically separated from air) and hydrogen (typically produced via SMR). Integration of ammonia production with the grid as a variable source of demand for grid balancing will require small-scale plants to be developed that can also fluctuate their output; ammonia plants today typically operate at relatively stable load. ARPA-E funds research on developing energy-dense liquid fuels from domestic resources, and technologies to convert those fuels into energy (e.g., fuel cells or internal combustion engines) or hydrogen for fueling stations.
5. **Professor Hong Yong Sohn** (*University of Utah*) presented on metals refining, specifically novel flash ironmaking technology (FIT) to produce non-pyrophoric DRI, or molten iron. DRI is an alternative to reducing iron ore by the traditional blast furnace approach, which requires coke, iron ore pellets, and limestone and has substantial emissions. DRI can be integrated with traditional steel refining operations or with electrical arc furnaces. The demand for DRI is increasing both in the United States and internationally. Professor Sohn explained how DRI can be produced with reducing gases, such as carbon monoxide and hydrogen, to significantly reduce the carbon dioxide emissions associated with steelmaking. Professor Sohn's research has been supported by the DOE's EERE's AMO with significant cost share by steelmaking companies through the American Iron and Steel Institute. Professor Sohn's presentation highlighted the progression of his research from laboratory-scale drop-tube furnace testing to a fully integrated particle-suspension pilot plant located on the campus of the University of Utah. He has shown that DRI can be produced from fine iron ore concentrate that is produced at an iron ore mine while mechanically separating gangue minerals (mainly quartz) from the iron oxide mineral. Taconite ore produced in Minnesota and Michigan can be processed and used in the FIT process without first being pelletized and sintered, as is normally required for the conventional blast furnace ironmaking process. The suspension reactor in FIT provides an adequate thermal and gas/ore contact zone to effectively "flash" reduce the iron ore concentrate to iron. FIT promises to reduce the large equipment and capital cost that is required for traditional integrated steel plants and other DRI process methods. Professor Sohn is hopeful that FIT can be commercialized in the near future.

Questions from Audience

1. *How much does hydrogen have to cost to be competitive in flash ironmaking?*

The team at the University of Utah is still evaluating this, but the price for hydrogen in industry ranges widely. Assumptions range from $1-$2/kg.

2. *What disruptive technologies in hydrogen could change the industry in the next 10 years?*

   Hydrogen production processes that can beat SMR in terms of cost would be game-changing. Additionally, developments in information technology that allow plants to align with partners in decision-making and improve their operations will be important. Within manufacturing, the ability to manufacture new structures cost-effectively (e.g., 2-D fabrication or 3-D printing of steel parts using iron parts) will be transformational.

3. *What impact would a carbon tax have on hydrogen prices?*

   The cost of hydrogen produced by electrolysis depends on the price of electricity, while the cost of hydrogen produced by SMR depends on the price of natural gas. A carbon tax would increase the price of natural gas, giving electrolysis a better value proposition.

4. *What is the potential for ammonia use in fuel cell vehicles?*

   We know that fuel cells can run on ammonia. Producing the ammonia efficiently and cleanly remains a challenge.

Additional Comments from Audience

- Natural gas is a bridge to using hydrogen in clean steelmaking. Midrex has 70 plants operating around the world with DRI technology that relies on natural gas. The first plant in the United States was commissioned last year in Corpus Christi and now produces over 1 million tonnes per year of DRI. Switching from natural gas to hydrogen in these plants would be relatively easy.
- We should consider the value proposition of H2@Scale in developing countries also facing pollution challenges, such as China and India. They may be willing to partner with and serve as the first implementers of H2@Scale concepts.
- We should develop an online resource to track environmental and energy policies in each state.
- Small modular liquefaction is important to integrate liquid carriers (e.g., liquid hydrogen) with the grid.
- We should explore demonstrations in Texas, where wind power and steelmaking are abundant (e.g., in Corpus Christi).

Summary of Breakout Session Results

The objective of the Day 1 breakout sessions was to 1) discuss the role of government, industry, and academia in addressing R&D, economic, and policy barriers to wide-scale deployment of clean hydrogen, and 2) to identify priority needs in R&D that will enable implementation of the H2@Scale vision.

The Day 1 breakout sessions were divided into three different topic areas to identify opportunities for and barriers to:

- Integrate hydrogen production with the electric grid (Breakout 1)
- Develop value-add applications of hydrogen, and integrate them with hydrogen production markets (Breakout 2)
- Expansion of hydrogen delivery infrastructure.

On Day 2, breakout participants discussed opportunities and barriers to using hydrogen from electrolysis in end-use applications (chemicals, fuels, and metals refining)

All breakout sessions brainstormed potential paths forward that enable H2@Scale.

In addition to the end-use application breakouts on Day 2, two of the Day 1 groups held follow-on discussions about developing an H2@Scale roadmap. That feedback is summarized in the H2@Scale Roadmap Discussions section.

The following six sections summarize the breakout results:

1. Incorporating hydrogen production with current and future power generation
2. Integrating value-add applications of hydrogen in current and future markets
3. Infrastructure needs for wide-scale deployment of hydrogen
4. Industrial end use of hydrogen for chemicals
5. Industrial end use of hydrogen for fuels
6. Industrial end use of hydrogen for metals refining.

Breakout 1: Incorporating Hydrogen Production with Current and Future Power Generation

The "Incorporating Hydrogen Production with Current and Future Power Generation" breakout session on Day 1 focused on the challenges and recommended actions associated with orders-of-magnitude increases in electrolyzer capacities and production volumes, and dynamic integration of electrolyzers with the U.S. energy infrastructure.

While the intent was to focus on the role of hydrogen in our grid infrastructure, the overall discussion was broadened somewhat due to the expertise of the group overall.

Table 1. Breakout on Electrolyzer Integration with U.S. Energy Infrastructure

Challenges/Barriers	Next Steps/Actions/Opportunities
Technological	
Valuation of H_2 in the infrastructure	Develop and apply tools for valuation of H_2 in the infrastructure and include long-term value streams, not just capital costs.
Technology readiness for large scale-up	Multi-MW demonstrations should be conducted that are market-based, commercially viable, and focused on regional needs. These demonstrations should show that H_2 can address the power curtailment problem at larger scales than batteries. Ideas for demonstrations that could guide R&D included integrating multi-ton liquefaction to variable generation, and thermochemical or high-temperature electrolytic H_2 generation. Near-term technology development needs and entry markets for large-scale electrolysis must be identified. Applications where use of H_2 creates a monetary/ performance benefit (e.g., forklifts) should be identified and studied. One example may be that managing curtailment by producing H_2 and transporting it through pipelines is a more acceptable alternative to building more power transmission lines; both of these approaches can manage curtailment, but the general public may be opposed to construction of new overhead transmission lines, but less opposed to construction of underground hydrogen pipelines. Medium- and heavy-duty transportation (e.g., buses) are another application that should be developed. Additionally, the power-to-gas concept should be better understood (e.g., how much H_2 can be blended without affecting end users). International collaborations will be critical to assure U.S. technology and systems integration demonstrates the latest in science and engineering research.
Regulatory	
Need for stable and consistent long-term policy to drive the adoption of H_2—both in terms of research and	Utility Integrated Resource Plans are a way to drive local, specific plans to integrate H_2 into utility long-term plans. Mandates that require the use of H_2 (like the mandates for ethanol use in fuel) may be necessary to show the public that H_2 production is safe and

policies that drive utility involvement	effective. Inclusion of H_2 in LCFS, for example, could create a path for hydrogen growth. Policies are necessary that reward forward-thinking in energy. Adopt policies that drive significant shifts versus incremental changes in infrastructure. Advocacy is necessary to educate the policy community. The H_2 community should engage strongly with public utilities commissions.
Education	
The story of H_2 in our energy system must be clearer, more focused, and more cohesive	Revise flow diagram used in the “H2@Scale” presentations to convey priorities or near-term versus longer-term transitions. Develop a comprehensive “State of the State of Hydrogen” document. Develop a roadmap with near-term measurable milestones and broad stakeholder buy-in.

Breakout 2: Integrating Value-Add Applications of Hydrogen in Current and Future Markets

The "Integrating Value-Add Applications of Hydrogen in Current and Future Markets" (Value Added) breakout session on Day 1 focused on the long term opportunities and key first steps for including value-added applications of hydrogen in the H2@Scale vision.

Participants were asked to answer the following questions: "Regarding the long-term H2@Scale vision you heard today, what other long term opportunities should be included in the vision?" and the follow-on "What are the key first steps…?"

The breakout group included 25–30 participants with the following backgrounds: academic researchers, industry (metal production, energy, automotive, electrolysis), national laboratories, and local states.

The opportunities can be divided into three sections: Technology, Market and Economics, and Education. Table 2 contains the topic areas with barriers identified. **Green** text indicates higher priority topics, and **Purple** text indicates topics that generated greater discussion.

Table 2. Breakout on Integrating Value-Add Applications of H_2 in Current and Future Markets

Challenges/Barriers	Next Steps/Actions/Opportunities
Technology	
Lower cost of H_2	Production of H_2 at the point of use Production of H_2 from near-term sources. Examples include separation/recovery of H_2 from chemical processes where it is a byproduct, and steam reforming of biogas. Reduction in electrolyzer balance of plant costs through standardization, modularization, and R&D on H_2 compatibility of materials Materials and stack development to enable CO_2 co-electrolysis Utilization of by-products from H_2 production and use (e.g., O_2 byproduct from electrolysis and heat from fuel cells). This may require development of technologies and infrastructure for safe capture, storage, and transportation of O_2 Analysis to characterize availability and location of curtailed electricity, and potential role of H_2 carriers Partnership with National Network for Manufacturing Innovation to lower costs of electrolyzer manufacturing
Development of value-add applications for H_2	Development of modular systems for H_2 use. This may require manufacturing technologies to lower cost of producing high volumes of small-scale systems.

	Conversion of natural gas appliances to allow them to operate at higher H_2 concentrations R&D to develop materials based on low-cost H_2 that can be used in place of oil and natural gas-based materials (e.g., replacing polyethylene and polypropylene with plastics from H_2) R&D to replace conventional technologies that have emissions with H_2 (e.g., replace coke gas with H_2 in ironmaking and steelmaking) Use of FCEVs to provide power to houses. Customers may be willing to pay a premium for FCEVs if they have supplemental advantages like this. Demonstrations that provide lessons learned in real-world environments should be conducted. Examples could include: • Chemical processes where H_2 is a byproduct • Use H_2 and O_2 from electrolyzer in a power plant • Deploy electrolyzer where natural gas is not as readily available as H_2 • Make H_2 from biogas for fuel cell lift trucks
Market and Regulatory	
Market pull needs to be developed	One sector or technology needs to be very successful and cost effective at adoption/increase of H_2 use to create new infrastructure and incentivize greater market pull. This will likely not come from vehicles, but from distributed power generation. Identify key locations with needs for energy storage and grid services Analysis to identify and quantify key figures of merit (e.g., characterizing cost of H_2 per service provided, rather than $/kg) Assigning a “green” designation to products made with renewable H_2 to monetize customers willing to support clean H_2 production.
Regulatory framework must be developed	Rate structures that support use of otherwise curtailed electricity Policies that ascribe a value to green H_2 and renewable natural gas. Regulatory structures exist in Europe, for example, to incentivize blending of H_2 in natural gas Development of policies that offset the costs of renewable H_2. Inclusion of H_2 in Renewable Fuel Standard (RFS), and/or inclusion of efficiency metrics in RFS (since use of H_2 in fuel cells provides an efficiency advantage).
Transition current infrastructure to H_2	Conversion strategies to help companies that have already made large investments in existing infrastructure (e.g., steel pipelines) Ensure H2@Scale Roadmap incorporates infrastructure requirements,

	especially with respect to regulations. Long duration storage will be desirable, but needs to be included in planning and available early.
Regional job creation	Identify industries/regions that could be negatively impacted by growth in H_2, and develop programs to assist them in the transition.
Education	
Acceptance and vision of the future	The average person is unaware of the uses and potential of H_2, and there are a lot of misunderstandings regarding its use. The merits of H_2 need to be communicated in a simple, clear way to non-technical audiences. Competitions (like Solar Decathlon) should be conducted
Safety training	Average consumer must be educated to use H_2 safely Authorities having jurisdiction, first responders, and media should be educated on safety

Breakout 3: Infrastructure Needs for Wide-Scale Deployment of Hydrogen

The "Infrastructure Needs for Wide-Scale Deployment of Hydrogen" breakout session on Day 1 focused on the technical barriers and policy issues related to the distribution infrastructure for hydrogen.

The current state was defined as bimodal with truck transport of compressed gas and liquid hydrogen to distributed low-consumption customers and localized pipeline distribution to dedicated high use customers. The former is typified as vehicle fueling stations while the latter would be petroleum and chemical plants. It was also recognized that many high-consumption customers produce hydrogen on site for their own internal use.

Three distinct forms of distribution were identified as (i) regional, (ii) national and (iii) global distribution. Currently, only regional transport is widely used, but it was recognized that national and global transport will be required in the long term.

Table 3. Breakout on Expansion of Distribution Infrastructure for H_2

Challenges/Barriers	Next Step/Action/Opportunity
Technology	
Global distribution/transport of H_2	Advances in small-scale cryogenic technologies are necessary Liquid carriers should be re-evaluated to address their potential. Dehydrogenation catalysts have not kept up with advances in electrocatalysis over the past 20 years.
Blending of H_2 in the natural gas pipeline infrastructure could be detrimental to end uses. End uses (e.g., turbines and other rotational machinery) were not designed to run on H_2, and appliances are not as efficient when running on H_2 vs. natural gas	Differences between H_2, natural gas, and mixtures of the two gases with respect to heating values, flame speeds, and kinetics must be determined to assure safe use
Materials compatibility issues and differences between thermodynamics of H_2 vs. natural gas (e.g., flame speed) could limit the potential for H_2 blending in natural gas pipelines	
Large scale (1000s kg/day), high pressure interstate pipelines require larger compression equipment H_2 compression is notably inefficient currently	Design and build and assure the long term durability of very large scale compression equipment Design turbo-compressors for H_2 Recover the mechanical and thermal work imparted into high-pressure gas systems Extract thermal energy as gas temperature rises during compression and introduce step down turbines

	to recover mechanical energy upon decompression
Fuel quality requirements will ultimately dictate the economics of delivery, and will need to balance the consequences of contamination from shared assets with the cost of fuel separation and clean-up	Develop gas purification technologies to provide the purity required for the specific end use of the purchaser, particularly if depleted oil reservoirs are used for storage
Market	
Economic global distribution/transport of H_2	Utilize large-scale liquefaction with ocean-going ship transport, similar to current petroleum and liquefied natural gas markets
Economic regional/nationwide distribution/transport of H_2	Compressed gas, liquid H_2, ammonia, and liquid organic carriers are all viable in this space. Shipping forms and quality specifications should be standardized, however, to facilitate economies of scale. Standard interfaces, pressures, and volumes would also facilitate end use integration
Creation of a national pipeline network, similar to that used for natural gas distribution, is the desired long term state, but there is a high cost to install a dedicated pipeline network	Mitigate cost by co-locating this network with the current natural gas right-of-way Engage utilities in pipeline investments. Utilities can make long-term (10–20 year) investments, and may be able to write off of the substantial installation cost of a pipeline over long time frame.
Injecting H_2 into natural gas pipelines is uneconomical for the pipeline operator because pipeline rates are based on the energy content of the fuel, and hydrogen has a lower Btu content than natural gas	Consider incentives for mixing H_2 with natural gas Identify specific pathways dedicated to H_2 blending in natural gas
Long-term distributed storage (like that used in the natural gas pipeline network) will be necessary to accommodate potential temporal swings in H_2 demand l to accommodate customer needs	Line packing can be used to an extent Geologic storage is another manner of large scale storage: 1. Salt caverns—regionally located in the south and would be able to provide marginally pure product with little contamination 2. Depleted oil fields a. Issues with purity, leakage, and lost product are possible and would need investigation b. Many depleted oil and gas reservoirs have multiple drill heads, and all of these would need to be capped and sealed to minimize hydrogen loss
Lack of skilled H_2 distribution workforce	Scale up H_2 infrastructure incrementally, demonstrating profitability and job creation at each step Develop workforce as part of the technology

	implementation process 1. Build the required skilled workforce upon the current natural gas work force 2. Co-development of natural gas and H_2 technologies would work concurrently to provide this workforce
Renewable integration	Purely renewable sources not required for early implementation of H2@Scale Sectors familiar with existing compress gas technology may be early adopters of H_2, as they will have an easier time adapting to another compressed gas technology
Policy	
Natural gas pipelines have not been designed to transport H_2	The numerous ferrous and polymeric components in the pipeline system would have to be certified for use in a mixed natural gas/ H_2 environment
Regulations, codes, and standards	Develop regulations, codes, and standards early If policy dictates the use of specific renewable H_2 content, set standards and certifications to assure the renewable content of a H_2 supply
Demonstrations	Target early demonstrations and deployments: a. Regions where H_2 is already being used and where some infrastructure is already in place, such as California for transportation or Texas for petrochemical production b. Regions where local regulations favor the use of H_2 as an alternative fuel, such as California, the northeastern states, and Hawaii Locate demonstrations in varied customer, policy, and production environments a. This would exercise a diverse set of distribution technologies and lead to the most economic outcomes over the varied environments in which renewable H_2 will be produced, distributed, and utilized

Breakout 4: Industrial End Use of Hydrogen for Chemicals

The "Industrial End use of Hydrogen for Chemicals" breakout session on Day 2 focused on market opportunities for hydrogen use in the chemical industry (not including primary metals production) and the associated barriers and challenges.

The value proposition of hydrogen is complex and varied. Market opportunities for hydrogen use in the chemical industry (not including primary metals production) are available at different scales:

- Relatively large consumers of hydrogen that produce ammonia or ammonia-based fertilizer, methanol, or commodity chemical feedstock to make plastics and resins from petroleum derivatives
- Moderate-size markets for hydrogen include the glass making industry, the food processing industry, and niche chemicals
- Small-scale consumers of hydrogen (yet high value) include pharmaceutical chemicals and the electronics industry.

In the short term, process intensification and tweaks into existing processes are desired. In the long term newer, more direct processes are desired.

Table 4. Breakout on Use of Hydrogen in the Chemical Industry—Opportunities

Ammonia
a. Domestic and global demand for ammonia will rise significantly when nascent markets are realized for energy crops to produce biofuels and biopower b. New ammonia uses are on the rise: 1. Use for NOx selective catalytic reduction in coal and natural gas power plants 2. Diesel exhaust fluids that are now required for heavy duty trucks and mining vehicles c. Distributed demand for ammonia can create distributed demand for H_2 especially due to the benefits of colocation 1. Distributed ammonia plants may be more cost competitive for small quantity users 2. Distributed ammonia plants will greatly reduce the hazards of shipping, storage, and handling of ammonia by small-scale consumers.
Methanol and Other Organic Chemicals
a. Direct reduction of CO_2 with H_2 (CO_2 hydrogenation) as an alternative for methanol production (as well as higher alcohols and oxygenate chemical derivatives) b. Concept of *power to products* 1. Overcome hydrogen storage issues by storing H_2 within chemical bonds of more easily stored or transported molecules 2. Scheme can be tailored to deliver H_2 and co-production of other, perhaps multiple, chemical product streams
Other Chemical Industry Opportunities

a. Modular H_2 production systems

1. Manufacturing of chemicals from H_2 is a possible alternative to H_2 storage as it relates intermittent production of H_2 during seasons when there is excess electricity generation capacity
2. Distributed, smaller H_2 generation and specialty chemicals, which are high value and typically smaller production, can provide ways to de-risk the various H_2-related technologies as well as provide manufacturing analysis and shorter development cycles
3. Modular H_2 production systems allow one to change more readily with feedstocks or markets or technologies (i.e., adaptability is higher)

b. Low-cost large-scale H_2 production:

1. Could provide a business opportunity to relocate the chemical industry to H_2 generation sites as an alternative to H_2 delivery and storage. This can already be seen in industry when H_2 users are located near chlor-alkali plants where H_2 is produced as a by-product.
2. Various H_2 consumers could be co-located in "energy parks"

H2@Scale proposes to replace hydrogen generated by SMR with hydrogen generated by electrolysis. The workshop participants recognized that the great challenge is competition with the relatively low cost of hydrogen by SMR. Clearly, the single largest barriers are cost and convenience. Electrolysis needs to be simple to operate, safe to operate, and able to produce hydrogen in the quantity and quality needed.

- **Ammonia production for distributed use.** New process concepts, new catalysts, and new reactor development are needed for smaller, distributed plants. The Haber-Bosch process is mature, but it is based on tight integration with SMR and may not be as efficient when coupled with electrolysis processes. Overall for distributed systems, any new designs need to be scalable.
- **Methanol and other chemicals.** Techno-economic assessments of new routes to chemical production need to be completed to understand the business case for these alternatives. Subsequently, new catalysis and new reactor designs may be needed. Different metrics may also have to be developed to characterize small-scale units (e.g., $/system instead of $/kg), since costs of small scale systems are driven more by capex and not opex.
- **Electronics fabrication and pharmaceutical chemical production.** Electrolysis is already used, given the need for highly pure hydrogen and the relative cost and convenience of hydrogen production versus the product value. However, with the advent of H2@Scale, hydrogen costs may help reduce the marginal cost of products if hydrogen storage can be cost-effectively and safely used to ensure a steady supply of hydrogen is available.

Table 5 summarizes the technological, regulatory, and market transformation barriers identified by the breakout participants and proposed next steps to address these barriers.

Table 5. Breakout on Use of Hydrogen in the Chemical Industry—Barriers and Next Steps

Challenges/Barriers	Next Steps/Actions/Opportunities
Technology	
Functional and operational feasibility	Physics-based transient modeling Modeling and simulation using embedded controls logic and design optimization methods
Chemical synthesis process improvement and re-design evaluation Process integration with electrolysis (electrohydrogenation)	Process design and simulation models
Autonomous or remote control of distributed plants	Distributed control system test beds Instrument and controls development and demonstration Resilient and cyber-secure control verification
Scalability of smaller scale generators and systems Compact reactor designs for small and mini-scale NH_3 reactors	
Catalysts for micro-channel reactors, etc. Roust catalysts for transient and cyclic operation	Catalyst development and performance testing Catalyst manufacturing
Solid-oxide electrolysis cell (SOEC) development, production, and performance testing SOEC stack design and materials performance testing	Aid industry with SOEC and cell-stacks development and manufacturing Independent testing of commercially available SOEC for co-electrolysis operational mode
Market	
Specialty chemical synthesis	Examination of different chemical opportunity spaces including stranded markets Examine site-specific co-production of chemicals from different feedstocks. One example would be the business case for local electrolysis with captive H_2 and O_2 used to produce various chemical feedstocks
Alternative design concepts and overall systems	Plant design, economic pro forma, and life-cycle analysis
First-of-kind plants are considered too risky for investment	Bench-scale demonstration of state-of-the-art will address commercialization risks

	Modular designs, and mass manufacturing of these designs
Policy	
H_2 storage by industry needs to meet OSHA and other industry standards	Need a credible method to calculate associated benefits of using clean H_2 for consumer products
Incentives are necessary for electrolytic H_2	Begin addressing policy barriers with the transportation sector, because at least the transportation sector has LCFS. Leverage social acceptance of products produced from electrolytic H_2. Policy that enables customers to pay a premium for electrolytic H_2 would be beneficial. This is the so-called "green premium" in the commodity chemical business.

Breakout 5: Industrial End Use of Hydrogen for Fuels

The "Industrial End Uses of Hydrogen for Fuels" breakout session on Day 2 focused on the barriers and next steps for incorporating renewable hydrogen into the United States as an end-use fuel.

Approximately 30 people—a combination of government representatives, industry, and academics—attended the breakout session. The highest attendance seemed to be from industry, including various energy and utility companies.

This table summarizes additional opportunities for integrating renewable hydrogen in fuels.

The following table summarizes some of the technological, regulatory, and market transformation barriers and proposed next steps for incorporating renewable hydrogen into the United States as an end-use fuel.

Table 6. Breakout on Industrial End Use of Hydrogen for Fuels

Challenges/Barriers	Next Steps/Actions/Opportunities
Technology	
Cost of renewable H_2	R&D to lower the capital cost of large-scale electrolyzers
Reliability and scale of renewable H_2	R&D and demonstration to develop and prove the viability of large-scale electrolyzers
Risk of H_2 compatibility with existing natural gas pipeline	R&D to address pipeline compatibility Evaluate end use natural gas burners for both industrial and home use Blending H_2 into natural gas pipelines requires further analysis of materials compatibly and safety of end uses, including industrial and home burners
Market	
Public and industrial acceptance	High-profile public acceptance demonstration of synthetic fuels, or large-scale electrolysis (e.g., pilot for dairy or biomass industries) Engage potential advocates to help with public and industrial acceptance. Industrial gas companies may be interested in making H_2 from biomass, for example. Incorporate renewable H_2 into processes used for synthesis of existing liquid fuels, such as gasoline; e.g., hydro-desulfurization, hydrogenation, and deoxygenation a. Electrolytic H_2 has to be available at competitive cost, reliability, and scale. Refineries will not convert to electrolysis if it risks reliability.
Targeting regions and markets where electrolytic H_2 may be advantageous	Explore applications with remote locations that could be isolated in terms of grid or other pipelines a. H_2 for energy storage and micro-grid stabilization b. Petroleum refining in remote tar sands

Valuation of electrolytic H_2	Create a Sustainability Index that companies such as mutual funds can use for incorporating sustainability in long-term investments Conduct techno-economic analysis of current uses of H_2 (instead of distant future uses), accounting for global demand. One example would be the business case for refineries, with sensitivity to future regulatory scenarios, including RFS and LCFS. Conduct long-term economic analysis, accounting for the potential for customers to benefit from by-products of H_2 production (e.g., O_2 in the case of electrolysis or carbon from SMR); applications include oxy-combustion of fuels that require carbon capture and sequestration, medical application, biogasification, and steel processing. Include cost incentives for grid stabilization.
Policy	
H_2 is not accounted for in many existing policies for renewables	Amend RFS to be based on the CO_2 intensity of a fuel, and to incorporate hydrogen such that use of hydrogen (e.g., in syngas) also generates Renewable Identification Numbers Engage potential advocates of incentives for electrolytic hydrogen: a. Industrial gas companies may be interested in modifying RFS to include hydrogen b. State of California and potentially other states with Renewable Portfolio Standards c. Regions of the country with curtailment issues where hydrogen for energy storage could be utilized Assign credits for incorporation of renewable hydrogen into traditional non-renewable fuels (e.g., renewable H_2 into methanol, gasoline, or pipeline natural gas) Operators of natural gas pipelines will require economic incentives to blend H_2 into existing lines

Breakout 6: Industrial End Use of Hydrogen for Metals

The "Industrial End use of Hydrogen for Metals" breakout session on Day 2 focused on market opportunities for hydrogen use in the metals refining industry and the associated barriers and challenges. Two groups representing the steel industry participated in this breakout. Other participants included an air separations company and an inventor of a new, more efficient SMR process for hydrogen production.

National infrastructure is a general driver of economic growth and stability and national security. Yet, the United States has lost ironmaking and steelmaking markets for plate, pipe, and structured steel for building infrastructure, including pressure vessels for refineries and nuclear reactors. Clean hydrogen for DRI in the United States could reestablish U.S. markets in ironmaking and steelmaking. H2@Scale would replace coke, and thereby also replace coke gas and/or methane with hydrogen-enriched reducing gas and combustion fuels.

H2@Scale could be game changing for the metals industry for two important reasons:

1. The steel industry is energy intensive and emission are expensive to control; DRI can produce high quality steel and steel alloys that are used to make pressure vessels for the petrochemical industries, nuclear reactors, and the food processing industry
2. Domestic production of steel and associated upstream minerals production, and downstream metal products fabrication industries could provide several million middle class jobs in the United States.

Participant in this breakout session noted the following opportunities to implementing hydrogen as feedstock for iron ore reduction:

- DRI practiced by MIDREX is already considered mature and being commercialized.
- Using hydrogen would simplify the hardware needed at a steelmaking plant. Pressurized H_2 could reduce the size of DRI reactors, which would reduce capital costs, but also may enhance DRI reactions.
- Smaller markets that currently use delivered H_2 could be early adopters.
- There is interest in using oxygen co-produced from electrolysis, especially in metals processing.
- Steelmaking plants could create a large demand for H_2. The average steelmaking plant would use ~275,000 kg-H_2/day.

Table 7. Breakout on Use of H_2 in Metals

Barriers	Next Steps
Technology	
Commercial plant risk Using H_2 would require new systems design	Continue to support basic R&D on lab scale and pilot scale, such as the small pilot-plant demonstration at the University of Utah Build and demonstrate process in an appropriate scale pilot plant
Metals and alloys annealing and tempering in H_2-rich flames Metals rolling, milling, and forming and joining testing, quality assurance/quality control and codification	Materials chemical, metallurgical, and mechanical properties assay (strength, corrosion, creep fatigue, stress-crack, etc.)
Market	
Risk and cost of using electrolytic H_2 in steelmaking	Evaluate business case for DRI steelmaking, using H_2 and O_2 from electrolysis Pilot-scale demonstration of FIT and other DRI processes such as the MIDREX process Plant design, economic pro forma, and life-cycle analysis
Policy	
Policy that monetizes social acceptance of products that use clean H_2	Need a credible method to calculate associated benefits of using clean H_2 for consumer products

H2@Scale Roadmap Discussions

During the Day 1 breakout sessions it became clear that a roadmap is needed to congeal broad stakeholder agreement on a path forward to achieve the H2@Scale vision by 2050. On Day 2 of the workshop, two of the Day 1 breakout groups—hydrogen production and infrastructure—reconvened to focus on aspects of such a roadmap for the production, distribution, and grid-use of hydrogen at scale.

- What would measures of progress and success look like?
- What are the high priority next steps?
- What does the timeline look like?

Progress and Success Measures

The hydrogen production group discussed the need to identify measurable indicators of progress toward a hydrogen-intensive energy infrastructure. Possible measurable indicators include the following:

- H_2 production technology:
  - Amount of electrolytic H_2 produced annually
  - Overall emissions reduction enabled by H_2 systems
  - Costs on several levels, including lifetime or levelized cost of H_2 production as well as capital and operating costs
    - Effective baselines of present-day associated costs must be established.
    - The value of avoided curtailment must be quantified to fully measure the value of hydrogen
- Market support:
  - Annual public and private investment amounts in H_2 commercial and research sectors
  - Levels of renewable energy curtailment nationally (e.g., in MWh) over a given timeframe
  - Number of hydrogen-related jobs—both absolute and newly-produced
  - The size of the hydrogen industry and related infrastructure, and market share of hydrogen in related industrial sectors
  - The success and impact of hydrogen marketing, perhaps adapting metrics from other industries, and utilizing such organizations as H2USA for guidance and support
- Policy:
  - Legislation on hydrogen—both quantity and quality—at local, state, regional, and federal levels

The infrastructure group discussed that the development of a roadmap to bring the distribution aspects of H2@Scale to fruition will require:

a. Rigorous definition of (a) the current state and (b) the final projected state
b. An understanding of the various production and utilization methods that will be predominant in the economy.

A roadmap should assess both long range transport of electrical energy for applications where solely electrical energy is used for hydrogen generation, and the long distance transport of hydrogen gas where hybrid thermochemical systems are used for hydrogen generation. This assessment needs to be conducted in coordination with both of these teams within H2@Scale.

Priorities

The hydrogen production group identified a set of high-level priorities for an H2@Scale Roadmap:

1. Of key importance was the notion of focus: select ***up to three*** top-priority industrial sectors and/or value streams and focus near-term efforts on commercial viability related to those.
2. Early success was deemed important to create momentum for long-term impacts.
3. Technology goals include the notions of demonstrating efficiency increases and reduced costs along these industrial lines.
4. Demonstrations were clearly regarded as an important aspect of a viable roadmap that will bring about fundamental changes and order-of-magnitude increases related to hydrogen and the electric grid.
   a. Demonstrations should be designed to focus on regional aspects of hydrogen production, storage, and end use in key sectors.
   b. As the group envisioned a year 2025 status update on H2@Scale, it was stated that at least three functioning large-scale demonstrations would be operating and showing measurable results along several objectives using the metrics designated above.

Proposed H2@Scale Timeline

The hydrogen production group participated in a forward-looking visualization exercise to illuminate near-term priorities needed to enable significant long-term goals. Specifically, participants were asked to identify changes that will be needed by the year 2020 to enable the H2@Scale future of 2050.

Some of the themes discussed include:

1. Focus on fuel cell cars and trucks for early market entry
2. Have a complete roadmap in place with which the industry is on board

3. Identify market areas that will have significant consumer demand
4. Work to influence federal decision makers over the next year, as the groundwork for federal budgets is laid at least two years in advance.

The infrastructure group brainstormed a timeline to achieve the three aspects of H2@Scale: (a) production, (b) distribution, and (c) customer development. Determining how to achieve these states will require a more rigorous study than could be accomplished at this meeting.

H2@Scale Future Timeline[35]

(Infrastructure Breakout Session Brainstorm on Technology Pathways)

2020

- Production: SMR
- Distribution: local hydrogen pipeline, liquid hydrogen and compressed gas trucking, natural gas pipeline packing, localized pipelines, electrical transmission
- Customers: California transportation, Northeast transportation, Texas chemical industry, Hawaii integrated industries

2030

- Production: SMR/electrolysis, integrated with the grid
- Distribution: state pipeline systems, liquid hydrogen and compressed gas trucking
- Customers: California transportation industry, Texas chemical and power generation industries

2040

- Production: SMR/thermochemical/electrolysis, grid integration of electrolysis
- Distribution: regional pipelines, isolated local pipeline networks, liquid hydrogen and compressed gas trucking
- Customers: nationwide transportation industry, Midwest industrial sector, residential sectors

2050

- Production: thermochemical/electrolysis, grid integration of electrolysis
- Distribution: interstate pipeline network, local pipeline network, liquid hydrogen, international shipping
- Customers: integrated widespread utilization

[35] This timeline indicates the technologies that were expected to dominate the hydrogen market within the expected timeframes. For example, in the near-term, SMR is expected to be the dominant form of hydrogen production. Projections for the mid-term and long-term were based on expectations of R&D making new technologies feasible.

Appendices: Technical Deep-Dives

The following appendices provide background on key technical aspects of H2@Scale, for the interested reader.

Appendix A: Technical Background on the Power Grid

In recent years, the majority of new electrical generation capacity installed in the United States has been wind and solar power.[36] While the growth in renewable electricity generation has many benefits, the inherently intermittent and "non-dispatchable" nature of these resources presents challenges to grid operation.

In electricity grids, the supply of electrical power at any given instant must equal the sum of the demand and transmission losses. The grid has traditionally been powered by centralized fossil fuel and nuclear-powered turbomachinery and by hydroelectric generators. These generators typically rotate at the grid frequency (60 Hz in the United States). When the supply of electrical power is less than the demand, the excess demand will convert some of the rotational inertia of these generators into power, causing the generators to slow and the grid frequency to drop. When supply is greater than demand, the excess power speeds up the grid-tied generators, and the grid frequency rises. Large deviations in grid frequency (greater than about 0.02 Hz is considered significant) can damage various end-use equipment.

The traditional method to regulate grid frequency has been to vary or "dispatch" the output of fossil-fueled and hydroelectric generators to match variations in demand and transmission losses. Nuclear power plants face operational challenges in dispatching their output on relevant timescales.[37] Alternatively, the electrical output of inflexible power generators can be curtailed when supply exceeds demand, which results in financial losses for these generators. Finally, transmission capacity can be increased to increase the pool of flexible generators within a certain area, though increasing transmission capacity can be challenging and has limited benefit beyond a certain penetration of inflexible generation.[38] As a greater fraction of the total generating capacity on the grid is comprised of wind and solar power, there are fewer remaining dispatchable resources to manage imbalances in electricity supply and demand. Already, multiple nuclear power plants have closed in the United States due to the challenges resulting from the priority grid access given to renewable energy over other generation types.[39,40] The deployment of high- and low-temperature electrolyzers to produce hydrogen from water, nuclear or renewable electricity and (in some cases) nuclear heat feedstocks presents a solution to this problem.

The utility of electrolyzers for grid stability is multifaceted. On short timescales (on the order of tens of microseconds), if supply is greater than demand and there is no alternative option but to curtail renewable and nuclear power generation, electrolyzer power use can be increased to maintain grid frequency. Under these circumstances, increasing electrolyzer power demand results in no marginal increase in grid emissions. Alternatively, if the power supply suddenly

[36] "Wind adds the most electric generation capacity in 2015, followed by natural gas and solar," *Today in Energy*, U.S. Energy Information Administration, March 23, 2016, https://www.eia.gov/todayinenergy/detail.php?id=25492.

[37] B. Levau, "EDF aims to have two-thirds of French reactors in load-following mode this year," *Nucleonics Week* 16-Jun-2016 (2016): 5-6.

[38] P. Denholm and M. Hand, "Grid flexibility and storage required to achieve very high penetration of variable renewable electricity," *Energy Policy* 39 (2011): 1817-30.

[39] M. Mobilia, "Fort Calhoun becomes fifth U.S. nuclear plant to retire in past five years," *Today in Energy*, U.S. Energy Information Administration, October 31, 2016, http://www.eia.gov/todayinenergy/detail.php?id=28572.

[40] H. Trabish, "How Electricity Gets Bought and Sold in California," *GreenTech Media*, March 29, 2012, https://www.greentechmedia.com/articles/read/How-Electricity-Gets-Bought-and-Sold-in-California.

becomes less than the demand, the power output of the grid-tied electrolyzers can be reduced.[41] The use of electrolyzers over diurnal cycles to absorb, for example, excess solar[38,42] or nuclear power[43] during times of excess generation has been suggested by multiple investigators. Similarly, beyond a certain total penetration of renewable energy (typically on the order of 50%), there exist large seasonal imbalances in power generation and demand.

If electrolyzers are used to handle seasonal imbalances in supply and demand on the grid, high-volume storage will be necessary for the hydrogen produced. An innovative approach to storing this hydrogen is to blend it with natural gas in existing natural gas pipelines. At low concentrations, hydrogen blending is expected to have minimal consequences to end uses of the natural gas.[44] An alternative approach is to produce fuels out of the hydrogen through electrochemical processes. For example, hydrogen can be combined with a carbon feedstock to generate synthetic natural gas via the Sabatier process or emerging electrochemical processes.[45] The Fischer Tropsch process can be used to generate liquid fuels from hydrogen and carbon feedstocks. The use of electrolyzers to produce hydrogen gas or hydrogen-based fuels allows for grid balancing in a manner that decouples the technology that takes power from the grid from the storage of that power. The ability to recouple energy storage from energy use can make electrolyzers far more economical and practical for grid balancing than batteries.

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[41] J. Eichman, K. Harrison, and M. Peters, *Novel Electrolyzer Applications: Providing More than Just Hydrogen* (Golden, CO: NREL, 2014), NREL/TP-5400-61758, http://www.nrel.gov/docs/fy14osti/61758.pdf.

[42] J. Williams et al., *Pathways to Deep Decarbonization in the United States*, the U.S. report of the Deep Decarbonization Pathways Project of the Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations (San Francisco: Energy and Environmental Economics, Inc., 2014), revision with technical supplement, Nov. 16, 2015.

[43] C. Sink, "High Temperature Nuclear Reactors for Hydrogen Production" (presented at the Hydrogen and Fuel Cell Technical Advisory Committee Meeting, Arlington, VA, November 18-19, 2014), https://www.hydrogen.energy.gov/pdfs/htac_nov14_4_sink.pdf.

[44] M. Melaina, O. Antonia, and M. Penev, *Blending Hydrogen into Natural Gas Pipeline Networks: A Review of Key Issues* (Golden, CO: NREL, 2013), NREL/TP-5600-51995, http://www.nrel.gov/docs/fy13osti/51995.pdf.

[45] M. Singh, E. Clark, and A. Bell, "Thermodynamic and achievable efficiencies for solar-driven electrochemical of carbon dioxide to transportation fuels," *Proceedings of the National Academy of the Sciences* (2015): E6111-18.

Appendix B: Technical Background on Electrolyzers

Electrolyzers are used to produced hydrogen and oxygen from water using electricity. Several different types of electrolyzer technologies are currently on the market or under development. These technologies are usually distinguished by the material used for the electrolyte or membrane. They can also be distinguished by operating temperature range, which is usually categorized as "low temperature" (<100°C) and "high temperature" (>600°C) electrolysis. Low temperature electrolysis is dominated by liquid alkaline (potassium hydroxide), PEM, and alkaline exchange membrane (AEM) technologies. The leading high temperature electrolysis technology currently under development is SOEC.

The cost of electricity dominates the cost of hydrogen production via electrolysis; electricity can account for up to 75% of electrolysis cost.[46] However, the cost of electricity is expected to fall as penetrations of intermittent generation on the grid increase, allowing for production of lower cost hydrogen.[47] As the cost of electricity falls, reductions in capital cost will become increasingly important for electrolyzers to compete economically with SMR.

Liquid alkaline (e.g., potassium hydroxide) electrolyzers are the most mature technology and have been commercially available for many decades. PEM electrolyzers have been used for years, primarily at small scales (e.g., 1–100 kg/day), in applications where delivery of hydrogen from centralized production is not economical or practical (e.g., laboratories, submarines, or power plants located far from natural gas resources) or where high-purity hydrogen is necessary. A current focus for the PEM electrolyzer industry is the development of manufacturing technologies to:

1. Scale electrolyzers to megawatt scales, such that they can be used as a form of demand response for grid stability and energy storage
2. Enable low-cost, high-volume production of electrolyzers to meet growing demand
3. Implement recent R&D advances in PEM electrolyzer stack components (e.g., electrodes that require 5–10 times less platinum group metals [PGM] than today's commercial products to achieve equivalent or superior performance[48]) in commercial products.

An additional R&D need is the assessment of the impact of intermittent operation on the durability of low-PGM electrodes. While electrodes with high loadings of PGMs appear to be capable of tolerating intermittent operation,[49] reductions in PGM loading will be necessary to reduce cost.

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[46] "Hydrogen Production Cost From PEM Electrolysis" (Washington, DC: DOE Hydrogen and Fuel Cells Program, 2014), Program Record 14004, https://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf.

[47] B. Pivovar, "H2@Scale Overview" (presented at the H2@Scale Workshop, Golden, CO, November 16-17, 2016), https://energy.gov/sites/prod/files/2016/12/f34/fcto_h2atscale_workshop_pivovar_2.pdf.

[48] E. Miller, "Hydrogen Production & Delivery Program" (plenary presentation at the 2015 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Arlington, VA, June 8-12, 2015), https://www.hydrogen.energy.gov/pdfs/review15/pd000_miller_2015_o.pdf.

[49] M. Peters et al., "Renewable Electrolysis Integrated System Development and Testing" (presented at the 2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Washington, DC, June 6-10, 2016), https://www.hydrogen.energy.gov/pdfs/review16/pd031_peters_2016_o.pdf.

AEM-based electrolyzers are currently at low technology readiness levels but offer the potential for lower capital cost than is achievable with PEM electrolyzers. The AEM environment is basic (unlike the acidic environment of PEM electrolyzers) and therefore allows for the use of PGM-free catalysts and a wider range of materials options for bipolar plates. Initial demonstrations of PGM-free AEM electrolysis at the cell level, which helps to substantiate the low cost benefits[50] have been successfully performed; however, significantly more R&D needs to be carried out to demonstrate this technology's full potential and to achieve the performance and durability required to compete with commercial electrolyzer technology.

SOEC electrolyzers are currently being researched due to their ability to operate at high temperatures, and therefore high efficiencies. Integrating SOECs with process heat from industrial processes, such as nuclear power generation, can lead to low cost hydrogen.[51] The ability of SOECs to respond quickly to fluctuations in power supply or heat supply still needs to be determined. While testing of SOEC cells and stacks has demonstrated excellent, efficient performance, the durability of these units must be improved significantly for them to be commercially ready.[52]

[50] K. Ayers, "High Performance Platinum Group Metal Free Membrane Electrode Assemblies Through Control of Interfacial Processes" (presented at the 2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Washington, DC, June 6-10, 2016), https://www.hydrogen.energy.gov/pdfs/review16/pd123_ayers_2016_o.pdf.

[51] "Hydrogen Production Cost from Solid Oxide Electrolysis" (Washington, DC: DOE Hydrogen and Fuel Cells Program, 2016), Program Record 16014, https://www.hydrogen.energy.gov/pdfs/16014_h2_production_cost_solid_oxide_electrolysis.pdf.

[52] R. Petri et al., "Solid Oxide Based Electrolysis and Stack Technology with Ultra-High Electrolysis Current Density (>3A/cm2) and Efficiency" (presented at the 2016 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Washington, DC, June 6-10, 2016), https://www.hydrogen.energy.gov/pdfs/review16/pd124_petri_2016_o.pdf.

Appendix C: Technical Background on Hydrogen Infrastructure

Hydrogen is supplied to industrial end users today in three different ways: pipelines, liquid tankers, and gaseous tube trailers. The United States currently has nearly 1,600 miles of hydrogen pipelines that are almost exclusively made of steel,[53] operate at maximum pressures of about 70 bar,[54] and primarily supply the petrochemical industry. Due to their high capital cost, pipelines are generally only installed in areas with end users whose demand is hundreds of thousands of kilograms per day[55,56] and is expected to be stable for at least 20–30 years. Recent and ongoing FCTO R&D on pipelines aims at lowering their capital cost through the codification of novel materials, such as fiber-reinforced polymer, and characterization of conventional materials, such as high-strength steels, in hydrogen service under the loading conditions that would be expected in a mature FCEV market.

Liquid tankers and tube trailers are used where demand is not large or predictable enough to warrant the capital costs of pipeline construction. Liquid tankers can carry about five times as much hydrogen as tube trailers today.[57] Their use is inhibited, however, by the cost of liquid hydrogen and the risks of boil-off. Conventional liquefaction processes rely on compression, expansion, and throttling,[58,59] all of which generate irreversible losses of energy that inhibit efficiency and drive cost. Additionally, liquid hydrogen vaporizes (i.e., “boils off”) over time if cryogenic equipment is not well-insulated and used regularly. End users of liquid hydrogen must therefore be prepared to use the hydrogen within reasonable time frames, and to optimize their operations to minimize heating.

Gaseous tube trailers are used for maximum payloads of about 720 kg and/or when a customer will be using the hydrogen as a pressurized gas. For example, hydrogen fueling station operators may prefer to receive hydrogen in a gaseous trailer because they must ultimately dispense the hydrogen as a gas at 700 bar pressure. The amount of energy the station will expand compressing hydrogen to 700 bar will be less if the gas is received in a high-pressure, gaseous form. The maximum pressure of hydrogen tube trailers on the market today is about 500 bar. These tube trailers require special permits from the U.S. Department of Transportation due to their weight.

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[53] “Pipeline and Hazardous Materials Safety Administration Portal,” U.S. Department of Transportation, https://portal.phmsa.dot.gov/analytics/saw.dll?Dashboard.

[54] J. R. Fekete, J. W. Sowards, and R. L. Amaro, “Economic impact of applying high strength steels in hydrogen gas pipelines,” *International Journal of Hydrogen Energy* 40 (2015): 10547-58, http://dx.doi.org/10.1016/j.ijhydene.2015.06.090.

[55] Praxair, “Praxair Expands Hydrogen Supply with Gulf Coast Start-Up,” news release, July 22, 2013, http://www.praxair.com/news/2013/praxair-expands-hydrogen-supply.

[56] “Air Products’ U.S. Gulf Coast hydrogen network” (Allentown, PA: Air Products and Chemicals, Inc., 2012), http://www.airproducts.com/microsite/h2-pipeline/pdf/air-products-US-gulf-coast-hydrogen-network-dataSheet.pdf.

[57] “Hydrogen Delivery,” in *Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan* (Washington, DC: U.S. Department of Energy, 2016), section 3.2, https://energy.gov/sites/prod/files/2015/08/f25/fcto_myrdd_delivery.pdf.

[58] U. Cardella, L. Decker, and H. Klein, “Large-Scale Hydrogen Liquefaction” (presented at the 26th International Cryogenic Engineering Conference-International Cryogenic Materials Conference 2016, New Delhi, India, March 7-11, 2016), http://icec26-icmc2016.org/downloads/8-O-1A-1.pdf.

[59] J. Essler et al., *Report on Technology Overview and Barriers to Energy- and Cost-Efficient Large Scale Hydrogen Liquefaction*, (Fuel Cells and Hydrogen Joint Undertaking, 2012), IDEALHY Project Task 1.1, http://www.idealhy.eu/uploads/documents/IDEALHY_D1-1_Report_Tech_Overview_and_Barriers_web2.pdf.

Geologic caverns are currently used to store high volumes of hydrogen (thousands of tonnes) to buffer short-term differences between hydrogen supply and demand. Hydrogen can be released from caverns with hours of notice, several times throughout a year. Caverns for gas storage are currently extracted from salt deposits, which are concentrated in the central and northeastern regions of the United States.[60] Four salt caverns, including the world's largest,[61] are currently operating in the United States and one in the United Kingdom.[60,62] In regions of the world where salt deposits are not available, caverns can be extracted from hard rock outcrops, provided that they are lined to prevent gas leakage. The world's only lined rock cavern for gas storage is currently operating in Sweden for storage of natural gas.[63]

Fueling stations for FCEVs are a rapidly growing market for hydrogen infrastructure. Installations of hydrogen fueling stations first began in the United States to support the market for fuel cell powered material handling equipment (i.e., forklifts).[64] Fueling stations for FCEVs are similar in design to those for forklifts, but require dispensing at higher pressures to ensure vehicle tanks can be completely filled within 3–5 minutes. Twenty-five (25) retail hydrogen stations for FCEVs are currently open in California, 19 of which were opened in 2016.[27] While stations in California are primarily being funded by the California Energy Commission, at least 12 industry-funded fueling stations are currently being planned for development in the Northeast, to support anticipated rollouts of FCEVs. Fueling stations are typically supplied hydrogen via gaseous tube trailers or liquid tankers from centralized production facilities, or they produce hydrogen onsite via electrolysis. Tube trailers are currently the most common option,[65] but liquid delivery is expected to become more economical as station capacities and utilization rates increase.[66]

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[60] A. S. Lord, P. H. Kobos, and D. J. Borns, "Geologic storage of hydrogen: Scaling up to meet city transportation demands," *International Journal of Hydrogen Energy* 39 (2014): 15570-82, http://dx.doi.org/10.1016/j.ijhydene.2014.07.121.

[61] Air Liquide, "USA: Air Liquide operates the world's largest hydrogen storage facility," press release, January 3, 2017, https://www.airliquide.com/media/usa-air-liquide-operates-world-largest-hydrogen-storage-facility.

[62] "Salt," Mineral Planning Factsheet (British Geological Survey, 2006), https://www.bgs.ac.**uk**/downloads/start.cfm?id=1368.

[63] L. Mansson and P. Marion, "The LRC Concept and the Demonstration Plant in Sweden – A New Approach to Commercial Gas Storage," (paper presented at the 22nd World Gas Conference, Tokyo Japan, June 1-5, 2003), http://members.igu.org/html/wgc2003/WGC_pdffiles/10167_1045823542_13005_1.pdf.

[64] "Industry Deployed Fuel Cell-Powered Lift Trucks" (Washington, DC: DOE Hydrogen and Fuel Cells Program, 2016), Program Record 16012, https://www.hydrogen.energy.gov/pdfs/16012_industry_deployed_fc_powered_lift_trucks.pdf.

[65] J. McKinney et al., Joint Agency Staff Report on Assembly Bill 8: Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California (Sacramento: California Energy Commission, 2015), CEC-600-2015-016, http://www.energy.ca.gov/2015publications/CEC-600-2015-016/CEC-600-2015-016.pdf.

[66] A. Elgowainy, K. Reddi, D. Brown, and N. Rustagi, "Hydrogen Delivery Infrastructure Analysis" (presented at the 2015 DOE Hydrogen and Fuel Cells Program Annual Merit Review and Peer Evaluation Meeting, Arlington, VA, June 8-12, 2015), https://www.hydrogen.energy.gov/pdfs/review15/pd014_elgowainy_2015_o.pdf.