New Industry Partnerships: Solar Energy Technologies Office Support for Early Projects in the Energy Systems Integration Facility—An Agreement Closeout Summary Report

Bryan Palmintier, Andy Hoke, Murali Baggu, Blake Lundstrom, Sudipta Chakraborty, Kevin Harrison, Nancy Dowe, John Lewis, Greg Stark, Mark Ruth, Tessa Greco, and Martha Symko-Davies

National Renewable Energy Laboratory

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The authors would also like to thank the large number of people involved with the success of each of the partnership projects and of the overall agreement. This includes the project teams from partner organizations, the multiple researchers and ESIF lab staff who conducted extensive research and analysis for these projects. Many of these contributors are included as co-authors in the papers and reports listed as part of each project summary. Special thanks to those who also contributed behind the scenes to set up experiments, develop and review safety practices, manage finances and reporting, and otherwise support these efforts. Special thanks to Ben Kroposki for his leadership with the ESIF facility and with gathering support from across EERE for this and related efforts and to Martha Symko-Davies for all of her efforts to establish and maintain the partnerships on this agreement along with many of the spin-off projects and countless other efforts in ESIF. Special thanks also to the multiple generations of leadership in SETO who supported this project, most recently including Guohui Yuan and Rebecca Jones-Albertus. Thanks also the NREL solar program team including Mary Werner, James Cale, Bryan Palmintier, and Barry Mather for their role as DOE liaisons. Thanks also to Robin Lovato for help with assembling an early draft of this report from multiple other sources. Special thanks to Tessa Greco for her help with assembling the original list of publications and other impacts used here. Thanks also to Katie Wensuc for editorial assistance and to Ben Kroposki, Keith Ropchock, and all of the report authors for their review and corrections to this summary report.

List of Acronyms

CVR	conservation voltage reduction
DMS	distribution management system
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
ESIF	Energy Systems Integration Facility
HECO	Hawaiian Electric Companies
ICT	information technology, communications, and telecommunications
IVVC	integrated volt/VAR control
LCOM	levelized cost of synthetic methane
NIP	New Industry Partnership
NREL	National Renewable Energy Laboratory
PEM	polymer electrolyte membrane
PF	power factor
PHIL	power-hardware-in-the-loop
PV	photovoltaics
S2G	solar to gas
SDG&E	San Diego Gas & Electric Company
SETO	Solar Energy Technologies Office
SoCalGas	Southern California Gas Company
VAR	volt-ampere reactive

Executive Summary

The U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy (EERE) Solar Energy Technologies Office (SETO)-funded New Industry Partnerships (NIPs) agreement established multiple new cooperative research projects with industry partners to accelerate the impact of the Energy Systems Integration Facility (ESIF) at the National Renewable Energy Laboratory (NREL) as a designated User Facility. Each project demonstrated the use of the National Renewable Energy Laboratory's ESIF as a national asset for research and development, testing, and validation of new technologies to support the optimization and impact of energy systems integration. The agreement was launched in late 2013 and represented the initial SETO portfolio in ESIF.

The NIPs agreement was a bit different from traditional research projects because it was specifically structured to enable partnerships for ESIF experimentation and as such required a 1:1 funds-in cost share from industry partners. In the end, the project engaged six different industry partnerships that provided $2M in funds-in cost share, plus an addition approximately $3M and over 2800 hours of in-kind cost share (including the donation of the bioreactor described in Project 6). These partnership projects resulted in evaluating several innovative technologies that utilized many of the laboratories in the ESIF to demonstrate a wide range of capabilities. These included small-scale inverters; power-to-gas technologies; and advanced simulation, analysis, and power-hardware-in-the-loop testing techniques. As a result, the agreement resulted in the key impacts of 1) building awareness and maturity of ESIF as a world-class research facility and 2) creating an ecosystem where researchers and industry can come together and collaborate to tackle integrated energy challenges. The agreement also provided significant impact metrics for both research and industrial communities, as summarized in Table ES-1 and outlined in this report.

Further, these projects catalyzed numerous spin-off projects resulting in tens of millions of dollars in additional industry support and providing the core base for a wide range of successful partnerships, utilization, and follow-on impact at the ESIF. Many of the partners from this agreement continue to partner with NREL to leverage the value provided by DOE's investment in the ESIF User Facility. The SETO program is acknowledged and thanked deeply for their investment and insights to making these partnerships possible and providing support to ESIF at a critical junction for success.

Table ES-1. Impact Summary of New Industry Partnerships Agreement

Journal Articles	Conference Publications	Conference Presentations	Workshops/ Webinars	Patents	Honors and Awards	Technical Reports and Other Publications	Software, Data Sets, or Hardware	Standards and Codes Input	Cost Share to NREL (Funds-in/ In-kind)	Spin-Off Projects	Spin-off Project Funding
5	13	22	12	2	1	10	4	2	$2M/$3M	9+	>$23M

In addition to these metrics, the projects resulted in many important qualitative impacts, including:

- Enabling regulatory changes to double the capacity of distributed solar photovoltaics (PV) eligible for fast interconnections
- Advancing planning approaches for PV-plus-storage
- Informing key updates to the Institute of Electrical and Electronics Engineers 1547 interconnection standard
- Influencing utility decisions to adopt advanced distribution management systems to help manage large quantities of solar on the grid.
- Influencing new business models on integration such as who is responsible when the inverter does not function.

This summary report provides a brief, high-level overview of these projects and their highlights along with lists of citations and other impacts. Readers are referred to the corresponding project reports for more in-depth information.

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1 SolarCity/Hawaiian Electric Companies

NREL PI: Sudipta Chakraborty

1.1 Overview

Leveraging the ESIF, SolarCity and Hawaiian Electric Companies (HECO) partnered with NREL to evaluate the performance of several small residential and commercial inverters to address industry concerns around transient overvoltage, anti-islanding, and coordinated generation curtailment. For transient overvoltage, inverters from different manufacturers were tested in the ESIF to determine the duration and magnitudes of transient overvoltages created during load-rejection and ground-fault conditions. The results gave the photovoltaic (PV) community stakeholders confidence that advanced inverters could mitigate transient overvoltage concerns. Following the evaluations at NREL, HECO cleared its interconnection queue and increased its limit for distributed PV from 120% of minimum daytime load to 250%, specifically citing NREL's report as a reason for this change in policy.

Additional evaluations examined the performance of active inverter-based anti-islanding detection in the presence of numerous other inverters on a single feeder. These power-hardware-in-the-loop (PHIL)-based tests evaluated anti-islanding capabilities with and without advanced inverter functionality enabled. This research was the first reported laboratory evaluations of multi-inverter, multi-point-of-common-coupling anti-islanding and helped to increase utility confidence for anti-islanding performance with high level of PV penetration. Additional work studied the impacts of distributed PV systems with reactive power control on conservation voltage reduction (CVR) and power quality.

Full details of this effort can be found in the technical reports and other publications listed in sections 1.3–1.6. Additional impacts—including partnerships, outreach activities, intellectual property created, and spin-off projects—can be found in Appendix A.

1.2 Highlights and Impacts

- This project demonstrated advanced PV inverter mitigation of transient overvoltage with large quantities of distributed PV.
- As a result, HECO removed a moratorium on PV interconnection and expedited the installation of solar PV systems on circuits with up to 250% of daytime minimum load (from the previous 120%) if the PV systems are installed with advanced inverters that meet stricter requirements.
- Reports indicate this immediately opened 5,000 new interconnection requests at HECO.

1.3 Technical Reports

S. Chakraborty. "Mitigating Interconnection Challenges of the High Penetration Utility-Interconnected Photovoltaic (PV) in the Electrical Distribution Systems: Cooperative Research and Development Final Report, CRADA Number CRD-14-563." NREL/TP-5D00-67466. November 2016.

A. Hoke. Nelson, B. Miller, S. Chakraborty, F. Bell, and M. McCarty. “Experimental Evaluation of PV Inverter Anti-Islanding with Grid Support Functions in Multi-Inverter Island Scenarios.” NREL/TP-5D00-66732. July 2016.

A. Hoke, A. Nelson, S. Chakraborty, J. Chebahtah, T. Wang, and M. McCarty. “Inverter Ground Fault Overvoltage Testing.” NREL/TP-5D00- 64173. August 2015.

A. Nelson, A. Hoke, S. Chakraborty, J. Chebahtah, T. Wang, and B. Zimmerly. “Inverter Load Rejection Overvoltage Testing.” NREL/TP-5D00-63510. February 2015.

F. Ding, A. Nagarajan, S. Chakraborty, M. Baggu, A. Nguyen, S. Walinga, M. McCarty, and F. Bell. “Photovoltaic Impact Assessment of Smart Inverter Volt-Var Control on Distribution System Conservation Voltage Reduction and Power Quality.” NREL/TP-5D00-67296. December 2016.

1.4 Journal Articles

A. Hoke, S. Nelson, S. Chakraborty, F. Bell, and M. McCarty. “An Islanding Detection Test Platform for Multi-Inverter Islands Using Power HIL.” *IEEE Transactions on Industrial Electronics*. 2018.

M. Ropp, A. Hoke, S. Chakraborty, D. Schutz, C. Mouw, A. Nelson, M. McCarty, T. Wang, and A. Sorenson. “Ground Fault Overvoltage with Inverter-Interfaced Distributed Resources.” *IEEE Transactions on Power Delivery*. 2016.

F. Ding and M. Baggu. “Coordinated Use of Smart Inverter with Legacy Voltage Control Devices in Distribution Systems with High Distributed PV Penetration—Increase CVR Energy Savings.” 2018.

A. Hoke, J. Giraldez, B. Palmintier, E. Ifuku, M. Asano, R. Ueda, and M. Symko-Davies. “Setting the Smart Solar Standard—Collaborations between Hawaiian Electric and the National Renewable Energy Laboratory.” *IEEE Power and Energy Magazine* (lead article). October 2018.

1.5 Conference Publications

A. Nelson, A. Hoke, B. Miller, S. Chakraborty, F. Bell, and M. McCarty. “Impacts of Inverter-based Advanced Grid Support Functions on Islanding Detection.” IEEE Innovative Smart Grid Technologies Conference. 2016.

A. Nelson, A. Hoke, S. Chakraborty, M. Ropp, J. Chebahtah, T. Wang, and B. Zimmerly. “Experimental Investigation of Load Rejection Over-Voltage from Grid-Tied Solar Inverters.” IEEE Photovoltaic Specialists Conference (PVSC). 2015.

F. Ding, A. Nguyen, S. Walinga, A. Nagarajan, M. Baggu, S. Chakraborty, M. McCarty, and F. Bell. “Application of Autonomous Smart Inverter Volt-VAR Function for Voltage Reduction Energy Savings and Power Quality in Electric Distribution Systems.” IEEE Innovative Smart Grid Technologies Conference. 2017.

1.6 Conference Presentations

A. Nelson, A. Hoke, B. Miller, S. Chakraborty, F. Bell, and M. McCarty. "Impacts of Inverter-based Advanced Grid Support Functions on Islanding Detection." IEEE Innovative Smart Grid Technologies Conference. 2016.

A. Nelson, A. Hoke, S. Chakraborty, M. Ropp, J. Chebahtah, T. Wang, and B. Zimmerly. "Experimental Investigation of Load Rejection Over-Voltage from Grid-Tied Solar Inverters." IEEE Photovoltaic Specialists Conference (PVSC). 2015.

F. Ding, A. Nguyen, S. Walinga, A. Nagarajan, M. Baggu, S. Chakraborty, M. McCarty, and F. Bell. "Application of Autonomous Smart Inverter Volt-VAR Function for Voltage Reduction Energy Savings and Power Quality in Electric Distribution Systems." IEEE Innovative Smart Grid Technologies Conference. 2017.

2 Duke Energy/Alstom Grid

NREL PI: Bryan Palmintier

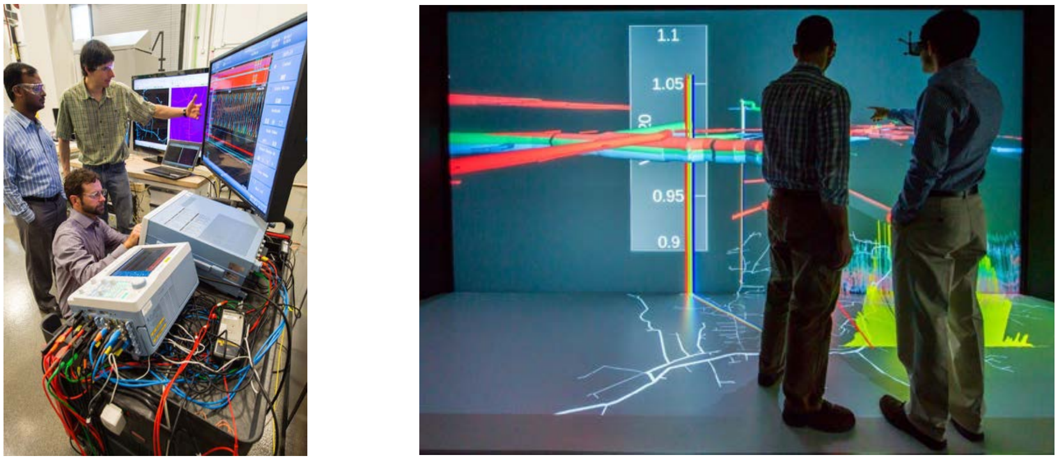

Figure 1. The Duke Energy/Alstom Grid partnership resulted in innovative PHIL testing of a 500-kVA advanced solar inverter (left) and first-of-their-kind 3-immersive 3D visualizations (right) to better understand the opportunities for DMS and advanced inverters to manage the interconnection of large amounts of distributed solar. ***Photos by (left) Dennis Schroeder, NREL 33983, and (right) Dennis Schroeder, NREL 34487***

2.1 Overview

From 2014–2016, Duke Energy, Alstom Grid (now GE Grid Solutions), and NREL collaborated to better understand advanced inverter and distribution management system (DMS) control options for large (1–5 MW) distributed PV and their impacts on distribution system operations. The specific goal of the project was to compare the operational—specifically, voltage regulation—impacts of three methods of managing voltage variations resulting from such PV systems:

1. Active power only (baseline)
2. Local autonomous inverter control: power factor (PF) ≠1 and volt/volt-ampere reactive (VAR) (Q(V))
3. Integrated volt/VAR control (IVVC) coordinated through the DMS to both manage voltage and reduce demand through CVR. IVVC was run with and without the PV system(s) included in the control scheme.

The project found that all tested configurations of DMS-controlled IVVC provided improved performance and provided operational cost savings compared to the baseline and local control modes. Specifically, IVVC combined with PV at a 0.95 PF proved the technically most effective voltage management scheme for the system studied. This configuration substantially reduced both utility regulation equipment operations and observed voltage challenges. On a cost basis, central IVVC (excluding direct PV control and only commanding existing/legacy utility equipment) performed slightly better than IVVC with PV at a 0.95 PF due to the latter's need to purchase more traditionally generated electricity to cover slightly higher system losses from increased reactive power flows. The operational cost savings for the IVVC scenarios were partially driven by reduced wear and tear on utility regulation equipment but were dominated by the use of CVR to reduce the need to purchase energy from traditional generation.

In addition, the project produced several other key insights and developed a wide range of new analytic approaches that have already provided the foundation for additional research and development efforts, specifically:

- Quasi-steady-state time-series simulations of system operations that directly use a commercial DMS system as the simulation engine, augmented by Python scripting for more detailed modeling of the PV inverter(s)
- Statistics-based methods to reduce simulation times by conducting detailed time-series analysis for only 40 days and then using these to estimate full-year results
- Advanced visualization to provide improved insights into time-series results and other PV operational impacts
- PHIL testing with a 500-kVA advanced inverter linked through co-simulation to full-scale feeder simulations in real time.

This effort pointed to the effectiveness of the IVVC for managing voltage with high levels of, megawatt-scale, distributed PV. In all scenarios tested, coordinating voltage regulation using the central DMS IVVC algorithm drastically reduced regulator operations while only modestly increasing capacitor switches and nearly eliminating load voltage challenges observed in the baseline; however, solving and implementing the IVVC algorithm every 10 minutes (or longer) might not be able to effectively regulate voltage effects caused by highly variable PV. More frequent IVVC solutions and/or including PV forecasting in IVVC are enhancements that could be further explored to address such issues. Sensitivity analysis highlighted the strong impact location has on the effectiveness of local PV controls and suggests increased value of local inverter control modes—particularly volt/VAR—with even higher levels of solar PV or when PV is located farther from the substation.

Full details of this effort can be found in the technical reports and other publications listed in sections 2.3–2.5. Additional impacts—including partnerships, outreach activities, intellectual property created, and spin-off projects—can be found in Appendix B.

2.2 Highlights and Impacts

- Demonstrated that DMS coordination can be more technically and economically effective than advanced inverters alone
- Developed advanced 3D visualization and statistical data analytic techniques to evaluate high levels of PV integration
- Developed and tested DMS co-simulation approaches with PHIL hardware testing, including the ESIF's first medium-voltage hardware-in-the-loop testing.

2.3 Technical Reports

B. Palmintier, J. Giraldez, K. Gruchalla, P. Gotseff, A. Nagarajan, T. Harris, B. Bugbee, M. Baggu, J. Gantz, and E. Boardman. "Feeder Voltage Regulation With High Penetration PV Using Advanced Inverters and a Distribution Management System: A Duke Energy Case Study." NREL/TP-5D00-65551. November 2016.

2.4 Conference Publications

A. Nagarajan, B. Palmintier, and Murali Baggu. "Advanced Inverter Functions and Communication Protocols for Distribution Management." 2016 IEEE PES T&D Conference and Exposition. Dallas, Texas. May 2016.

A. Nagarajan, B. Palmintier, F. Ding, B. Mather, and M. Baggu. "Improving Advanced Inverter Control Convergence in Distribution Power Flow." North American Power Symposium (NAPS). Denver, Colorado. September 2017.

B. Palmintier, B. Bugbee, and P. Gotseff. "Representative Day Selection Using Statistical Bootstrapping for Accelerating Annual Distribution Simulations." Integrated Smart Grid Technologies (ISGT) Conference. Arlington, Virginia. April 2017.

2.5 Conference Presentations

B. Palmintier, L. Ponder, and J. Gantz. "Mitigating Adverse Impacts of Distributed Solar PV with Smart Inverters & Integrated Volt-var Control." Alstom North American Users Group. Bellevue, Washington. June 3, 2015.

B. Palmintier, L. Ponder, and J. Gantz. "Mitigating Challenges with Distributed Solar PV via Smart Inverters & Integrated Volt-Var Control." DistribuTECH. Orlando, Florida. February 9, 2016.

A. Nagarajan, B. Palmintier, and M. Baggu. "Advanced Inverter Functions and Communication Protocols for Distribution Management." 2016 IEEE PES T&D Conference and Exposition. Dallas, Texas. May 2016.

A. Nagarajan, B. Palmintier, F. Ding, B. Mather, and M. Baggu. "Improving Advanced Inverter Control Convergence in Distribution Power Flow." North American Power Symposium (NAPS). Denver, Colorado. September 2017.

B. Palmintier, B. Bugbee, and P. Gotseff. "Representative Day Selection Using Statistical Bootstrapping for Accelerating Annual Distribution Simulations." Integrated Smart Grid Technologies (ISGT) Conference. Arlington, Virginia. April 2017.

3 Google Little Box Challenge

NREL PI: Blake Lundstrom

3.1 Overview

Through the Little Box Challenge, Google encouraged the development of advanced PV inverters with high power density by holding a public competition and offering a prize for the best performance. CE+T Power's Red Electrical Devils team won $1 million for their design of the highest power density, smallest form-factor inverter. Teams from Schneider Electric and the Virginia Tech Future Energy Electronics Center won honorable mentions. The winning inverters made use of wide-bandgap semiconductors to enable their power electronics to operate at higher voltages and temperatures, and hence manage more energy in a smaller volume.

Table 1. Results of the Three Top Teams in the Google Little Box Challenge

	CE+T Power's Red Electric Devils	Schneider Electric	Virginia Tech's Future Energy Electronics Center	Little Box Challenge requirements
Power Density (W/in^3)	142.9	96.2	68.7	>50
Volume (in^3)	14.0	20.8	29.1	<40

Google selected NREL as their evaluation partner for the contest, and the NREL team assisted with defining the contest's requirements; designing experimental configurations, test plans, and safe working procedures for the unique experiment; evaluating inverter prototypes from 18 finalist teams with typical solar inverter operating conditions exceeding 100 hours; and analyzing the large data set of results to help Google decide the winner of the contest. UL and other academic institutions were part of the development for setting the requirements.

The competition illustrated the potential to shrink inverters by an order of magnitude, which could make them cheaper to produce and install. The more compact technology can also enable more homes to adopt solar, support more efficient distribution grids, and potentially help bring electricity to remote areas. At the end of the day Google kept the IP and set new standards for this industry through their partnership in ESIF.

Additional information about the effort can be found in the publications listed in sections 3.3–3.6. Additional impacts—including partnerships, outreach activities, intellectual property created, and spin-off projects—can be found in Appendix C.

3.2 Highlights and Impacts

- Competitors successfully achieved an order-of-magnitude increases in power density with small-scale, 2kW inverters in 14–30 in^3 (baseball-softball size)
- Project resulted in highly publicized use of the ESIF for equipment evaluations and analysis in support of Google's Little Box Challenge
- NREL evaluated the efficiency and performance of the prototype inverters for 100 hours.
- Three of 10 teams met/exceeded targets: CE+T, Schneider Electric, and Virginia Tech.

- The project generated extensive media coverage for the event and of ESIF, including the 17 articles listed in Appendix C.

3.3 Technical Reports

B. Lundstrom. "The Google High Power Density Inverter Prize: Innovation in PV Inverter Power Density: Cooperative Research and Development Final Report, CRADA Number: CRD-14-568." NREL/TP-5D00-68287. May 2017.

3.4 Conference Publications

N. Ainsworth, B Johnson, and B Lundstrom. "A Fuzzy-Logic Subsumption Controller for Home Energy Management Systems." IEEE North American Power Symposium (NAPS). 2015. Charlotte, North Carolina. Published November 23, 2015. 978-1-4673-7389-0.

3.5 Conference Presentations

N. Ainsworth, B. Johnson, and B. Lundstrom. "A Fuzzy-Logic Subsumption Controller for Home Energy Management Systems." IEEE North American Power Symposium (NAPS). 2015. Charlotte, North Carolina. Published October 4–6, 2015.

3.6 Other Publications

B. Lundstrom. "Designing a Smaller Power Inverter: the Google Little Box Challenge." Video. https://www.osti.gov/scitech/servlets/purl/1372668. June 2016.

H. Lammers. ""Little Box Challenge" Inverters Arrive at NREL." Press Release. https://www.nrel.gov/news/press/2015/21584.html. October 2015.

H. Lammers. "NREL to Test Inverters for the "Little Box Challenge" Presented by Google and IEEE." Press Release. https://www.nrel.gov/news/press/2014/15400.html. September 2014.

4 San Diego Gas & Electric Company

NREL PI: Murali Baggu

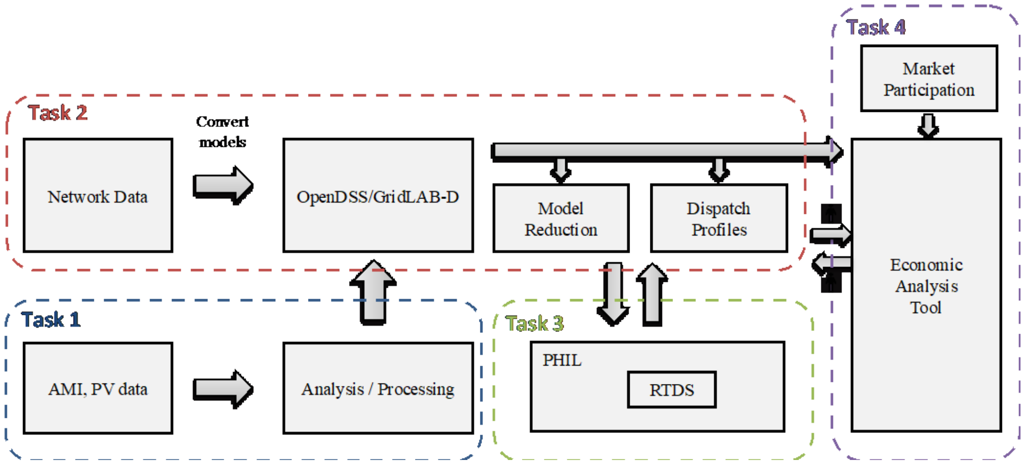

Figure 2. Modeling and testing flow for the SDG&E partnership

4.1 Overview

For this project, San Diego Gas & Electric Company (SDG&E) partnered with NREL for research and evaluation support in energy storage sizing and placement with real-time testing at both the SDG&E Integrated Test Facility (ITF) and in the ESIF. In addition to PHIL testing, the project developed advanced modeling and planning capabilities to manage PV and storage and to perform corresponding cost/benefit analysis based on a real microgrid scenario with a high levels of PV (existing in SDG&E's territory).

Additional information about this effort can be found in the publications listed in sections 4.3–4.5. Additional impacts—including partnerships, outreach activities, intellectual property created, and spin-off projects—can be found in Appendix D.

4.2 Highlights and Impact

- NREL researchers worked closely with SDG&E to help train them on the use of PHIL to evaluate deployment of PV in their service territory. Additionally, effort was provided to SDG&E in the development of their ITF.
- The project deployed cost/benefit analysis and modeling tools developed under the SunShot Solar High Penetration funding opportunity announcement (with APS).

4.3 Technical Reports

M. Baggu. "NREL and SDG&E Collaboration to Support SDG&E Grid and Storage Efforts: Cooperative Research and Development Final Report, CRADA Number CRD-14-562." NREL/TP-5D00-67668. January 2017.

4.4 Journal Articles

M. Baggu, A. Nagarajan, D. Cutler, D. Olis, T. Bialek, and M. Symko-Davies "Coordinated Optimization of Multiservice Dispatch of Energy Storage Systems with Degradation for Utility Applications." *IEEE Transactions on Sustainable Energy*. 2019.

4.5 Conference Publications

K. A. Smith, M. M. Baggu, A. Friedl, T. Bialek, and M. Robert Schimpe. "Performance and Health Test Procedure for Grid Energy Storage Systems." IEEE PES General Meeting. Chicago, Illinois. July 2017.

T. Harris, A. Nagarajan, M. Baggu, and T. Bialek. "Cost Benefit and Alternatives Analysis of Distribution Systems with Energy Storage Systems." 2017 IEEE 44th Photovoltaic Specialists Conference (PVSC). Washington, D.C. June 25–30, 2017.

N. Ainsworth, A. Hariri, K. Prabakar, A. Pratt, M. Baggu. "Modeling and Compensation Design for a Power Hardware-in-the-Loop Simulation of an AC Distribution System." 2016 North America Power Symposium. Denver, Colorado. September 2016.

A. Pratt, J. Wang, N. Ainsworth, K. Prabhakar, M. Baggu, T. Bialek and M. Symko-Davis "Evaluating Impacts of Battery Energy Storage System Functionalities on Distribution Systems Using Power Hardware-in-the-Loop Simulation" 2018 IEEE PES General Meeting, Portland, Oregon. August 5 – 10, 2018

5 SunPower

NREL PI: Blake Lundstrom

5.1 Overview

In this project, NREL researchers worked with SunPower to validate holistic PV-plus-storage inverter control using PHIL testing. This included evaluating the capability, efficiency, battery utilization, and system impacts when applied across an electric distribution system. The unit was tested in various operating modes, including PV smoothing, externally dispatched operation, scheduled operation, and self-consumption. The battery portion of the unit was further evaluated for performance under both normal operation and various extreme conditions to ensure proper operation. Hardware testing further included life-cycle evaluations of the battery system to provide hardware validation of a battery cell lifetime degradation model.

Additional information about this effort can be found in the publications listed in sections 5.3–5.5. Additional impacts—including partnerships, outreach activities, intellectual property created, and spin-off projects—can be found in Appendix E.

5.2 Highlights and Impacts

- Developed methods for evaluating the efficiency of multi-mode PV-battery inverters across their range of operation
- Evaluated the performance of a commercial 6.6-kW/11.67-kWh PV-battery inverter for on-grid to off-grid transitions.
- Demonstrated that using multiple, coordinated distributed PV-battery inverter units can provide a range of grid services, including voltage smoothing, reducing the number of tap change operations for utility voltage regulators, and reducing peak power requirements on the distribution system;
- Validated the performance of the battery management system and provided suggestions for improvement; and
- Developed a battery cell degradation model to predict the lifetime impacts of different PV-plus-storage operating modes.

5.3 Technical Reports

B. Lundstrom. "Residential PV-Energy Storage Testing Collaboration with SunPower: Cooperative Research and Development Final Report, CRADA Number CRD-14-569." NREL/TP-5D00-67463. November 2016.

B. Lundstrom and P. Gotseff. "Analyzing the Impact of Widespread DERs on Power Distribution Networks Using Data-Driven Models, Automated Scenario Building, and Integrated Power Hardware." NREL/TP-5D00-76753. 2021

5.4 Conference Publications

K. Smith, A. Saxon, M. Keyser, B. Lundstrom, Z. Cao, and A. Roc. "Life Prediction Model for Grid- Connected Li-ion Battery Energy Storage System." American Control Conference (ACC), 2017. Seattle, Washington. Published July 3, 2017.

P. Gotseff and B. Lundstrom. “Data-Driven Residential Load Modeling and Validation in GridLAB-D.” 2017 Ninth Annual IEEE Green Technologies Conference (GreenTech). Denver, Colorado. Published May 11, 2017.

5.5 Conference Presentations

K. Smith, A. Saxon, M. Keyser, B. Lundstrom, Z. Cao, and A. Roc. “Life Prediction Model for Grid- Connected Li-ion Battery Energy Storage System.” American Control Conference (ACC), 2017. Seattle, Washington. May 24–26, 2017.

P. Gotseff and B. Lundstrom. “Data-Driven Residential Load Modeling and Validation in GridLAB-D.” 2017 Ninth Annual IEEE Green Technologies Conference (GreenTech). Denver, Colorado. March 29–31, 2017.

6 Southern California Gas Company

NREL PI: Kevin Harrison

Figure 3. Installation (left) and fully assembled operation (right) of the SoCalGas bioreactor and supporting infrastructure at the ESIF. ***Photos by NREL***

6.1 Overview

This unique project partnership between NREL and the Southern California Gas Company (SoCalGas) explored the use of otherwise curtailed solar electricity to produce renewable methane (CH_4) that can then be used with long-duration storage, for direct end use, or as product feedstocks. It began with analysis of the potential impacts and then transitioned into hardware evaluation in ESIF. This effort focused on an innovative approach that combines an electrolyzer, a bioreactor, and the balance of plant to produce renewable natural gas from renewable hydrogen (H_2) and carbon dioxide (CO_2) using single-cell, self-replicating organisms. In general, solar to gas (S2G) represents an important opportunity to manage very high levels of solar. Converting excess solar electricity into a gaseous fuel, such as H_2 or CH_4, offers both a path for long-term seasonal storage and an additional revenue stream. In the near term, it can also increase the renewable energy content of the pipeline infrastructure—and hence all energy sectors, including industry and transport—while helping to address grid capacity, reliability, balancing, and curtailment challenges. In very high renewable grids, S2G could also help manage the seasonal mismatch between solar generation and demand by enabling access to the very large storage capacity that already exists in the natural gas network while also providing a low or zero net carbon fuel source for renewable combustion turbines (or fuel cells) that might be needed to replace existing fossil-fueled peaking facilities for reliability.

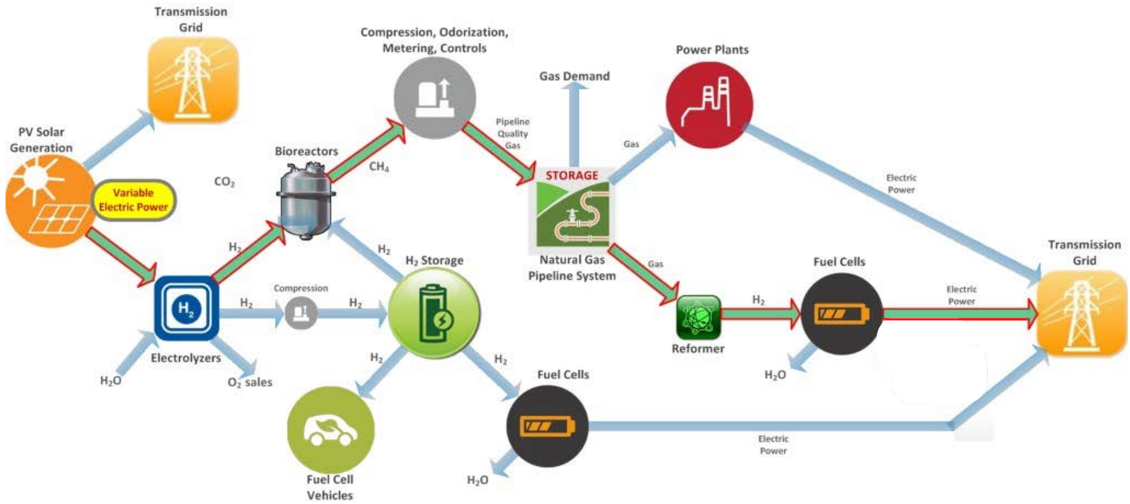

Figure 4. Conceptual diagram of S2G illustrating long-duration storage for grid and other applications

This partnership explored pilot-scale S2G operation, including evaluating performance under varying solar irradiance profiles and hydrogen production rates. To do so, this project helped fund the installation and initial testing of a 25-ft tall bioreactor and supporting equipment installed just outside the ESIF in 2017. Evaluation of the system began in 2018, after freeze protection and system commissioning.

Additional information on this effort can be found in the publications listed in Section 6.3 and through the lists of additional partnerships, outreach activities, intellectual property created, and spin-off projects found in Appendix F. The related effort in Project 7, described next, provides a techno-economic analysis of S2G to help identify cost/price targets.

6.2 Highlights and Impacts

- Developed detailed startup, shutdown (daily and extended), and safety processes for the bioreactor system.
- Started mapping the operational envelope of the bioreactor in terms of pressure ramp rates, temperature control, reactor level, mixing power, response time, gas input ranges, and methane production rates.
- Demonstrated the system response to changes in input gas flow rates and the ability for the control system to maintain the system pH, pressure, and temperature fluctuations during microbe growth and production activity phases.
- Developed sufficient monitoring and control software to achieve stable and safe operation of the system.
- Developed an understanding of technologies that can be used to produce renewable methane (CH_4) that can then be used as long-duration energy storage.

6.3 Conference Presentations

K. Harrison and N. Dowe. "Biology's Role in Energy Storage: A Unique 2-Step Process to Turn Renewable Electricity into Renewable Methane." Recent Advances in Fermentation Technology (RAFT12). Bonita Springs, Florida. October 2017.

K. Harrison. "H2 at Scale: Energy System-Wide Benefits of Increased H2 implementation." Alberta & Saskatchewan's Clean Energy Transition: Mapping Renewable Energy Market Restructuring & Development Initiatives. Calgary, Alberta. February 8, 2017.

K. Harrison. "H2 at Scale: Energy System-Wide Benefits of Increased H2 implementation." Alberta & Saskatchewan's Clean Energy Transition: Mapping Renewable Energy Market Restructuring & Development Initiatives. Calgary, Alberta. February 8, 2017.

K. Harrison and N. Dowe. "Biology's Role in Energy Storage: A Unique 2-Step Process to Turn Renewable Electricity into Renewable Methane." Recent Advances in Fermentation Technology (RAFT12). Bonita Springs, Florida. October 2017.

N. Dowe and K. Harrison. "Power-to-X: Utilizing Biological Gas Fermentation, Carbon Dioxide and Renewable Electricity to Produce Renewable Hydrogen, Methane, Chemicals and Other High-Value Products." International Conference on Energy Systems Integration, National Renewable Energy Laboratory, Golden, Colorado. December 5, 2017.

K. Harrison and N. Dowe. "Renewable Power-to-Renewable NG: Biological Methane Production." 7th Energy Storage and Renewable Integration Conference, Phoenix, Arizona. March 7, 2018.

P. Ghougassian. "Upgrading Biogenic CO2 to Methane Using Biomethanation and Power-to-Gas (P2G)." 2nd Germany California Bioenergy Symposium. Sacramento, California. September 20, 2019.

K. Harrison and N. Dowe. "Power-to-Gas: Renewable Hydrogen & Biomethanation—A Unique and Sustainable Approach to Renewable Fuels, Energy Storage and other Products." AIChE Annual Meeting. Orlando, Florida. November 11, 2019.

K. Harrison and N. Dowe. "Power-to-Gas: Renewable Hydrogen & Biomethanation—A Unique and Sustainable Approach to Renewable Fuels, Energy Storage and other High-Value Products." Colorado Cleantech Industry Association—Energy Connections: Creating Circular Fuels. Denver, Colorado. December 3, 2019.

K. Harrison. "What is the role of carbon fuels in the decarbonization journey?" Advanced Energy Conference Webinar. June 9, 2021.

K. Harrison. "Renewable Hydrogen Production and its Role in Long-Duration Energy Storage and Decarbonizing Fuels, Heat, Chemicals, and Agriculture." XXI International Congress of the Mexican Hydrogen Society. Virtual to Mexico City, Mexico. September 22, 2021.

7 Techno-Economic Analysis of Solar-to-Gas

NREL PIs: John Lewis and Mark Ruth

The final effort under this agreement conducted techno-economic analysis of S2G pathways. A summary of this analysis in included here. Detailed assumptions underlying this analysis relied on proprietary partner data, so the reader is referred to more recent efforts in this space through the H2@Scale and related programs.

7.1 Summary

A solar-to-methane (i.e., power-to-gas) scoping study was performed to investigate the levelized cost of synthetic methane (LCOM) production resulting from different envisioned operational scenarios and time frames. The goal of this analysis was to identify specific technology performance and cost targets that would enable a glide path from today's capabilities to operational scenarios based on expected future feedstock costs and performance. The examined system included a PV subsystem to generate renewable electricity to power a polymer electrolyte membrane (PEM) water electrolyzer for the production of hydrogen (H_2). The option for H_2 storage was investigated in one operational scenario to understand the cost impact of decoupling the operation of the PEM electrolyzer from the grid and downstream process. The generated H_2 would subsequently be fed to a bioreactor in combination with carbon dioxide (CO_2) collected from a colocated point source to biologically produce methane. Additionally, efforts were made to align analysis inputs in this study with previously published values from the Annual Technology Baseline; Multi-Year Research, Development, and Demonstration Plan; and State of Technology assessments to provide a bridge connecting existing analyses from the DOE EERE Solar Energy Technologies Office, Hydrogen and Fuel Cell Technologies Office, and Bioenergy Technologies Office.

7.2 Observations and Conclusions

The overarching goal of this analysis was to identify specific technology performance, feedstock, and production cost targets to transition from today's capabilities to operational scenarios based on expected future performance. Opportunities to decrease electricity costs and capital costs while increasing equipment capacity factors were identified as the primary needs to approach an LCOM of $15/MMBTU, a point estimated to be cost-competitive for renewable natural gas in rural, off-grid markets.

To approach an LCOM of $15/MMBTU, significant cost improvements were required across all technology subsystems. The combination of a levelized cost of electricity of $19/MWh, a levelized cost of hydrogen of $1.26/kg-$H_2$, and a levelized cost of bioreactor of $0.35/kg-$H_2$ was identified as one possible combination to achieve an LCOM of $15.34/MMBTU for produced renewable natural gas.

7.3 Future Analysis Opportunities

Specific future analysis opportunities identified during this initial scoping study included:

- Incorporate variable electricity pricing as a function of time of day into this analysis to investigate the effect of variable electricity pricing on process economics as well as overall system design and optimization.
- Investigate coupling PV and wind generation of renewable electricity to further decrease electricity costs and increase the PEM electrolyzer capacity factor without adding an energy storage option or grid support.
- Identify opportunities for improved integration of the PV and PEM electrolyzer subsystems to reduce the cost of power electronics and improve overall system electrical efficiency.
- Analyze additional system integration between the PEM electrolyzer and a wastewater treatment facility to use and monetize the oxygen (O_2) and low-temperature heat produced by the PEM electrolyzer. The wastewater treatment facility has chemical and biological O_2 demands as well as the need to maintain the operating temperature of the anaerobic digestor, typically ranging from 35°C–37°C.
- Perform a more detailed investigation and optimization of energy storage options (e.g., batteries vs. H_2) and storage locations within the system (e.g., energy storage before (batteries) or after the PEM electrolyzer (H_2storage)).
- Investigate an operational scenario with intermittent and variable flow of H_2 and CO_2 to the bioreactor to understand the impact of this mode of operation on the process economics.
- Test application of D3 renewable identification numbers and low-carbon fuel standard incentives that could further improve overall economics.

Appendix A. Additional Impacts and Outreach: Hawaiian Electric Companies/SolarCity

Project Partnerships

Partner Name	Partnership Type	Description of Partnership	Partner Investment ($)	Partner Value Add (In-Kind Commitment)
SolarCity	CRADA	Collaborative research on DER integration issues	$254k	1500 hours
Hawaiian Electric Companies	In-kind partner	Technical advisory role		300 hours
Forum on Inverter Grid Integration Issues	In-kind partner	Test plan development		1000 hours
Northern Plains Power Technologies	In-kind partner	Technical advisory role		
Electric Power Research Institute	In-kind partner	Technical advisory role		

Workshops/Webinars/Public Demonstrations

Title	Location	Date	# of Attendees
Inverter Anti-Islanding with Advanced Grid Support in Single- and Multi-Inverter Islands	Hawaii Smart Inverter Technical Working Group	August 16, 2016	50
Inverter-Based Ground Fault Overvoltage—Experimental Results	National Grid Distributed Generation Optimization Workshop	November 18, 2016	50

Software, Data Sets, or Hardware Developed

Name	Associated ROI/SWR
PQScal – Power Quality Score Calculation for Distribution Systems with DER Integration	Software Record SWR-17-37

Spin-Off Projects

Project or Cost Leverage Name	Description	Partner Investment ($) (If Applicable)	Partner Value Add (In-Kind Commitment)	Total Additional Project Value (Sum of Partner $, In-Kind, Additional $)
Hawaiian Electric Advanced Inverter Testing	TSA: PHIL evaluation of advanced inverters on Hawaii feeder models	$250k	1000 hours	$250k
VROS: Simulation of HECO Distribution Feeder Operations with Advanced Inverters and Analysis of Annual PV Curtailment	CRADA	$200k	1000 hours	$200k
VROS Pilot Project	CRADA Mod	$400k	1000 hours	$400k
Enphase Inverter Testing	TSA	$40k	800 hours	$40k

Standards and Codes Input

Standard/Code No.	Standard/Code Input	Version	Dates (or Status: In Review)
IEEE 1547	Provided technical basis for 1547 requirements on temporary and transient overvoltage with DERs	1547-2018	2018
IEEE 1547.1	LRO and GFO test procedures pioneered at NREL are being incorporated in modified form into 1547.1 test procedures.	1547-2020	2020

Media Coverage

Media Outlet	Title	Date	URL
IEEE Spectrum	Can Smarter Solar Inverters Save the Grid?	Oct. 20, 2016	https://spectrum.ieee.org/energy/renewables/can-smarter-solar-inverters-save-the-grid
Utility Dive	How the HECO-SolarCity Partnership Is Turning Rooftop Solar into a Grid Asset	Dec. 2, 2014	http://www.utilitydive.com/news/how-the-heco-solarcity-partnership-is-turning-rooftop-solar-into-a-grid-ass/338838/
Greentech Media	HECO and SolarCity to Put Smart Solar Inverters Through Real-World Testing	Dec. 8, 2014	https://www.greentechmedia.com/articles/read/heco-and-solarcity-to-put-smart-solar-inverters-through-real-world-testing#gs.yzdFeTg
Greentech Media	Hawaii's Utility Is Approving a Backlog of More Than 3,000 Solar Installations	April 1, 2015	https://www.greentechmedia.com/articles/read/hawaiis-utility-is-approving-a-backlog-of-more-than-3000-solar-installati#gs.uZObQ_4
GlobeNewswire	SolarCity, NREL and Hawaiian Electric Complete Inverter Study	Feb. 12, 2015	https://globenewswire.com/news-release/2015/02/12/705904/10119959/en/SolarCity-NREL-and-Hawaiian-Electric-Complete-Inverter-Study.html
PowerPulse.net	NREL Teams with SolarCity to Maximize Solar Power on Electrical Grids	Nov. 24, 2014	http://powerpulse.net/nrel-teams-with-solarcity-to-maximize-solar-power-on-electrical-grids/
PV Magazine	SolarCity's Hawaiian Study Reveals Grid Regulation Potential of Inverters	Feb. 12, 2015	https://www.pv-magazine.com/2015/02/12/solarcitys-hawaiian-study-reveals-grid-regulation-potential-of-inverters_100018207/
CleanTechnica	Test Results from NREL Spur Change In Penetration Limits For Solar Power In Hawaii	March 10, 2015	https://cleantechnica.com/2015/03/10/test-results-nrel-spur-change-penetration-limits-solar-power-hawaii/
CleanTechnica	NREL & SolarCity Join Forces in Hawaii	Nov. 27, 2014	https://cleantechnica.com/2014/11/27/nrel-solarcity-join-forces-hawaii/
Energy Manager Today	NREL Conducts Tests with SolarCity, Hawaiian Electric	Nov. 21, 2014	https://www.energymanagertoday.com/nrel-conducts-tests-solarcity-hawaiian-electric-0106884/
Metro Denver	Testing at NREL Aids Solar Power in Hawaii	Feb. 12, 2015	http://www.metrodenver.org/news/news-center/2015/02/testing-at-nrel-aids-solar-power-in-hawaii/
Science Daily	Advancing Solar Power in Hawaii	March 3, 2015	https://www.sciencedaily.com/releases/2015/03/150303123917.htm

Media Outlet	Title	Date	URL
Solar Daily	Testing at NREL Aids Solar Power in Hawaii	March 4, 2015	http://www.solardaily.com/reports/Testing_at_NREL_aids_solar_power_in_Hawaii_999.html
BizJournals.com	SolarCity, Hawaiian Electric Reach Agreement to Study Solar Interconnection Issues	Nov. 20, 2014	https://www.bizjournals.com/pacific/news/2014/11/20/solarcity-hawaiian-electric-reach-agreement-to.html
SolarLove.org	SolarCity & NREL Team Up in Hawaii	Nov. 24, 2014	http://solarlove.org/solarcity-nrel-team-hawaii/
Energy.gov	EERE Success Story—SunShot-funded Advanced Inverter Testing Enables 2,500 Solar Energy Systems to Connect to Hawaii's Electric Grid	Feb. 1, 2017	https://energy.gov/eere/success-stories/articles/eere-success-story-sunshot-funded-advanced-inverter-testing-enables

Appendix B. Additional Impacts and Outreach: Duke Energy/Alstom Grid

Honors and Awards

Recipient	Award	Sponsor	Date of Award
Final Technical Report	Selected as part of Distributed Energy Resources 101: Required Reading for a Modern Grid	Advanced Energy Economy	2017

Project Partnerships

Partner Name	Partnership Type	Description of Partnership	Partner Investment ($) (If Applicable)	Partner Value Add (In-Kind Commitment)	Subcontract Value to Partner (If Applicable)
Duke Energy	CRADA	50% cost-share partner	$425k		
Alstom Grid	Subcontract	Subcontract and in-kind cost share		$150k	$245k

Spin-off Projects

Project or Cost Leverage Name	Description	Additional Funding Source (Name, e.g., CEC, ESIF High Impact)	Project Value
ADMS Test Bed	The advanced distribution management system (ADMS) test bed is a national, vendor-neutral effort funded by the U.S. Department of Energy Office of Electricity's Advanced Grid Research Program to accelerate industry development and adoption of ADMS capabilities. The test bed enables utility partners, vendors, and researchers to evaluate existing and future ADMS, distributed energy resource management systems (DERMS), and other utility management system applications in a realistic laboratory environment.	DOE Office of Electricity	$2.8M initial funding, additional partnerships and funding in later phases

Appendix C. Additional Impacts and Outreach: Google

Project Partnerships

Partner Name	Partnership Type	Description of Partnership	Partner Investment ($) (If Applicable)	Partner Value Add (In-Kind Commitment)
Google	WFO (CRD-14-559)	Primary partner on the project. NREL worked very closely with the Google team to understand their needs for a distributed control system for managing DERs across a distribution system. Unfortunately, Google ended the project early because they decided not to pursue this area of development and shut down their internal program.	$190,000	$20,000
Google	WFO (CRD-14-568)	Primary partner on the Google Little Box Challenge testing effort. NREL worked closely with Google to help define contest requirements, review applications, and act as an independent third-party evaluation partner for the contest.	$176,134	
IEEE Power Electronics Society	Advisor	Google's official partner for the Google Little Box Challenge		

Workshops/Webinars/Public Demos

Title	Location	Date	# of Attendees
Google Little Box Challenge: Project Kick-Off Event	Energy Systems Integration Facility, NREL, Golden, CO, USA	Oct. 21, 2015	59

Media Coverage

Media Outlet	Title	Date	URL
EERE	EERE Success Story—NREL Partners with Google in Little Box Challenge	Mar 21, 2016	https://energy.gov/eere/success-stories/articles/eere-success-story-nrel-partners-google-little-box-challenge
IEEE Spectrum	Winning Google's Little Box Challenge Will Take a "Holistic Approach"	July 30, 2014	https://spectrum.ieee.org/energywise/energy/renewables/google-little-box-inverter-challenge
Forbes	Google's Little Box Challenge; A $1 Million Prize for Creating a Better, Smaller, Solar Power Inverter	May 20, 2014	http://www.forbes.com/sites/timworstall/2014/05/10/googles-little-box-challenge-a-1-million-prize-for-creating-a-better-smaller-solar-power-inverter/#549a81e93bad
CleanTechnica	Google's $1 Million Little Box Challenge: Invent a Smaller Thingy	July 24, 2014	http://cleantechnica.com/2014/07/24/googles-little-box-challenge-invent-a-smaller-inverter/
Greentech Media	Google's $1M Challenge: A Laptop-Sized Solar Inverter	July 23, 2014	http://www.greentechmedia.com/articles/read/googles-1m-challenge-a-laptop-sized-solar-inverter
ThinkProgress	If You Can Make Solar Power Better, Google Will Give You $1 Million	July 25, 2014	https://thinkprogress.org/if-you-can-make-solar-power-better-google-will-give-you-1-million-40dd7a469786/
Google Research Blog	And the Winner of the $1 Million Little Box Challenge Is…CE+T Power's Red Electrical Devils	Feb. 29, 2016	http://googleresearch.blogspot.com/2016/02/and-winner-of-1-million-little-box.html
Energy Matters	Google Announces "Little Box" Inverter Challenge Winner	March 2, 2016	https://www.energymatters.com.au/renewable-news/google-inverter-winner-em5364/

Appendix D. Additional Impacts and Outreach: San Diego Gas & Electric Company

Software, Data Sets, or Hardware Developed

- SWR 16-28 Analytical tools for modeling and visualizing impacts of emerging technologies in distribution feeders

Appendix E. Additional Impacts and Outreach: SunPower

Project Partnerships

Partner Name	Partnership Type	Description of Partnership	Partner Investment ($) (If Applicable)	Partner Value Add (In-Kind Commitment)
Sun Power Corporation	CRADA	Primary partner on the project. NREL worked closely with the SunPower team to review our work on all tasks, including residential PV-battery system performance evaluation, PHIL evaluation, battery management system evaluation, and battery lifetime model development	$212,500	$30,000

Software, Data Sets, or Hardware Developed

Name	Description	Version	Date	Additional Information
Battery Lifetime Prediction Model	Model for predicting the lifetime of a lithium-ion battery system given its configuration and operation profile	1.0	June 2016	Described in conference paper “Life Prediction Model for Grid—Connected Li-ion Battery Energy Storage System,” http://ieeexplore.ieee.org/abstract/document/7963578/
Residential Load Modeling Framework	Technique for creating residential load models based on field measurements. Useful for validating models vs. known cases and then having load models that can be used for wider simulation cases.	1.0	June 2016	Described in conference paper “Data-Driven Residential Load Modeling and Validation in GridLAB-D”, http://ieeexplore.ieee.org/abstract/document/7923933/

Appendix F. Additional Impacts and Outreach: Southern California Gas Company

Spin-Off Projects

Project or Cost Leverage Name	Description	Total Additional Project Value
ESIF High Impact project support for bioreactor.	Covers daily operations and characterization of the system performance.	$2.45M
Biopower project with partners: SoCalGas and Electrochaea GmbH	BETO funded, CRADA #: 18-00775, Goal: Biomethanation to upgrade biogas to pipeline grade methane.	$2.5M
Electrolyzer/Bioreactor Integration project with SoCalGas	BETO/SoCalGas/HFTO funded, CRADA #: 19-00809, Goal: Reduce to practice NREL IP that tightly integrates water electrolysis with downstream pressurized processes.	$4.4M
Biomethanation at a Dairy Digester project with partners Summit Utilities (Prime), SoCalGas, Plug Power, and Electrochaea GmbH	BETO/Summit Utilities/SoCalGas funded, CRADA, Goal: Relocate SoCalGas bioreactor to dairy digester in Maine to certify biomethanation process in carbon markets.	$10M

Media Coverage

- "Inventors Search for 'Missing Link' in Renewable Energy," John Fialka, E&E News reporter, Climatewire, Wednesday, January 17, 2018.
- "Novel Power-to-Gas Tech Begins Testing in the US," Katie Fehrenbacher, *Greentech Media*, October 16, 2017.
- "First US Biomethanation Reactor System for Power-to-Gas Testing Installed in Colorado," Dan McCue, *Renewable Energy Magazine*, October 13, 2017.
- "SoCal Gas, NREL Install Bioreactor for Pilot Power-to-Gas Project," *Renewables Now*, October 12, 2017.
- "Undersea Microbes Provide Path to Energy Storage," Wayne Hicks, NREL Feature Article, October 11, 2017.
- "NREL + Southern California Gas, Power-to-Gas Pilot Converts Electricity to Hydrogen, Stores it as Methane," NREL Fact Sheet, September 2017.
- "NREL and Southern California Gas Launch First U.S. Power-to-Gas Project," NREL Press Release, August 2017.

- “Batteries Can’t Solve the World’s Biggest Energy-Storage Problem. One Startup Has a Solution,” Akshat Rathi, *Quartz*, December 11, 2017.
- “SoCalGas Power-to-Gas Project Selected by U.S. Department of Energy’s National Renewable Energy Laboratory to Receive Funding,” Sempra Energy, April 24, 2017.
- “Are Ancient Bugs the Key to Storing Wind and Solar?” Stephen Lacey, Greentech Media podcast, October 15, 2019.

Workshops/Webinars/Public Demos

- K. Harrison. “Renewable Power-to-Renewable NG: Biological Methane Production.” Natural Gas Utilities—Downstream Natural Gas Initiative. Washington, D.C. April 18, 2018.
- K. Harrison and N. Dowe. “Biomethanation: A Unique and Sustainable Approach to Renewable Natural Gas.” Penn State Webinar Extension, Webinar #WBN-G-1252. June 28, 2018.
- K. Harrison. “Biomethanation: A Unique and Sustainable Approach to Renewable Natural Gas.” Southern Gas Association: Emerging Technologies. Denver, Colorado. August 8, 2018.
- K. Harrison. “Biomethanation: A Unique and Sustainable Approach to Renewable Natural Gas.” American Gas Association—RNG Workshop: Technology Outlook. Chicago, Illinois. August 30, 2018.
- K. Harrison. “Biomethanation: A Unique and Sustainable Approach to Renewable Natural Gas: A Partnership between Southern California Gas Company, Electrochaea and NREL.” RNG Works Technical Workshop & Trade Expo: The Coalition for Renewable Natural Gas. Denver, Colorado. September 12, 2018.
- K. Harrison. “Biomethanation: A Unique and Sustainable Approach to Renewable Natural Gas and other Products.” NREL Brown Bag Series. Golden, Colorado. February 13, 2019.
- K. Harrison. “How to Use Utility Pipelines to Store Electric Power: Discussing Power-to-Gas (P2G) & Utility Pipelines as the Better Battery.” RNG Works Technical Workshop & Trade Expo, RNG Coalition. Nashville, Tennessee. September 11, 2019.
- N. Dowe and K. Harrison. “Power-to-Gas: Biomethanation—A Unique and Sustainable Approach to Renewable Natural Gas and other Products.” American Gas Association/Environmental Protection Agency: Renewable Natural Gas Workshop. Reno, Nevada. September 24, 2019.
- K. Harrison and N. Dowe. “Power-to-Gas: Renewable Hydrogen & Biomethanation—A Unique and Sustainable Approach to Renewable Fuels, Energy Storage and other Products.” American Gas Association, Sustainable Growth Committee—Webinar. November 6, 2019.

Patents

- NREL Record of Invention No. 18-48:
    - Nonprovisional patent application
    - Publication no.: US 2021/0277343 A1
    - Application no.: 17/261,473
    - Filing date: September 9, 2021.
    - Licensed: This family of IP was exclusively licensed to Southern California Gas Company on 05/12/2020.
    - Converted to international (PCT) patent application PCT/US19/42861 and later nationalized in the U.S. as 17/261,473 on January 19, 2021
    - Other patent geographies are being pursued: Australia, South Korea, EPC (Europe), Israel, India, Canada, China, Saudi Arabia, Japan.
- NREL Record of Invention No. 19-140:
    - Nonprovisional patent application
    - Application no.: 17/397,665
    - Filing date: August 9, 2021
    - No current licensing agreement.