
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

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

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NOTICE

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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

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

This report is available at no cost from the National Renewable Energy Laboratory at www.nrel.gov/publications.
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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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


1.4 Journal Articles


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.


1.5 Conference Publications


1.6 Conference Presentations


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**

2.4 Conference Publications


2.5 Conference Presentations


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

<table>
<thead>
<tr>
<th></th>
<th>CE+T Power’s Red Electric Devils</th>
<th>Schneider Electric</th>
<th>Virginia Tech’s Future Energy Electronics Center</th>
<th>Little Box Challenge requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Density (W/in³)</td>
<td>142.9</td>
<td>96.2</td>
<td>68.7</td>
<td>&gt;50</td>
</tr>
<tr>
<td>Volume (in³)</td>
<td>14.0</td>
<td>20.8</td>
<td>29.1</td>
<td>&lt;40</td>
</tr>
</tbody>
</table>

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 in³ (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

3.4 Conference Publications

3.5 Conference Presentations

3.6 Other Publications


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
4.4 Journal Articles

4.5 Conference Publications


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


5.4 Conference Publications

5.5 Conference Presentations


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](image)

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 (CH₄) 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 (H₂) and carbon dioxide (CO₂) 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 H₂ or CH₄, 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.
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 (CH₄) that can then be used as long-duration energy storage.
6.3 Conference Presentations


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 is 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 (H2). The option for H2 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 H2 would subsequently be fed to a bioreactor in combination with carbon dioxide (CO2) 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-H2, and a levelized cost of bioreactor of $0.35/kg-H2 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 (O2) and low-temperature heat produced by the PEM electrolyzer. The wastewater treatment facility has chemical and biological O2 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. H2) and storage locations within the system (e.g., energy storage before (batteries) or after the PEM electrolyzer (H2storage)).

• Investigate an operational scenario with intermittent and variable flow of H2 and CO2 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

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

Workshops/Webinars/Public Demonstrations

<table>
<thead>
<tr>
<th>Title</th>
<th>Location</th>
<th>Date</th>
<th># of Attendees</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter Anti-Islanding with Advanced Grid Support in Single- and Multi-Inverter Islands</td>
<td>Hawaii Smart Inverter Technical Working Group</td>
<td>August 16, 2016</td>
<td>50</td>
</tr>
<tr>
<td>Inverter-Based Ground Fault Overvoltage—Experimental Results</td>
<td>National Grid Distributed Generation Optimization Workshop</td>
<td>November 18, 2016</td>
<td>50</td>
</tr>
</tbody>
</table>
## Software, Data Sets, or Hardware Developed

<table>
<thead>
<tr>
<th>Name</th>
<th>Associated ROI/SWR</th>
</tr>
</thead>
<tbody>
<tr>
<td>PQScal – Power Quality Score Calculation for Distribution Systems with DER Integration</td>
<td>Software Record SWR-17-37</td>
</tr>
</tbody>
</table>

## Spin-Off Projects

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

## Standards and Codes Input

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 1547</td>
<td>Provided technical basis for 1547 requirements on temporary and transient overvoltage with DERs</td>
<td>1547-2018</td>
<td>2018</td>
</tr>
<tr>
<td>IEEE 1547.1</td>
<td>LRO and GFO test procedures pioneered at NREL are being incorporated in modified form into 1547.1 test procedures.</td>
<td>1547-2020</td>
<td>2020</td>
</tr>
</tbody>
</table>
## Media Coverage

<table>
<thead>
<tr>
<th>Media Outlet</th>
<th>Title</th>
<th>Date</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greentech Media</td>
<td>Hawaii’s Utility Is Approving a Backlog of More Than 3,000 Solar Installations</td>
<td>April 1, 2015</td>
<td><a href="https://www.greentechmedia.com/articles/read/hawaiis-utility-is-approving-a-backlog-of-more-than-3000-solar-installations#gs.uZObQ_4">https://www.greentechmedia.com/articles/read/hawaiis-utility-is-approving-a-backlog-of-more-than-3000-solar-installations#gs.uZObQ_4</a></td>
</tr>
<tr>
<td>Media Outlet</td>
<td>Title</td>
<td>Date</td>
<td>URL</td>
</tr>
<tr>
<td>--------------------</td>
<td>----------------------------------------------------------------------</td>
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</table>
## Appendix B. Additional Impacts and Outreach: Duke Energy/Alstom Grid

### Honors and Awards

<table>
<thead>
<tr>
<th>Recipient</th>
<th>Award</th>
<th>Sponsor</th>
<th>Date of Award</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Technical Report</td>
<td>Selected as part of Distributed Energy Resources 101: Required Reading for a Modern Grid</td>
<td>Advanced Energy Economy</td>
<td>2017</td>
</tr>
</tbody>
</table>

### Project Partnerships

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

### Spin-off Projects

<table>
<thead>
<tr>
<th>Project or Cost Leverage Name</th>
<th>Description</th>
<th>Additional Funding Source (Name, e.g., CEC, ESIF High Impact)</th>
<th>Project Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADMS Test Bed</td>
<td>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.</td>
<td>DOE Office of Electricity</td>
<td>$2.8M initial funding, additional partnerships and funding in later phases</td>
</tr>
</tbody>
</table>
# Appendix C. Additional Impacts and Outreach: Google

## Project Partnerships

<table>
<thead>
<tr>
<th>Partner Name</th>
<th>Partnership Type</th>
<th>Description of Partnership</th>
<th>Partner Investment ($) (If Applicable)</th>
<th>Partner Value Add (In-Kind Commitment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Google</td>
<td>WFO (CRD-14-559)</td>
<td>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.</td>
<td>$190,000</td>
<td>$20,000</td>
</tr>
<tr>
<td>Google</td>
<td>WFO (CRD-14-568)</td>
<td>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.</td>
<td>$176,134</td>
<td></td>
</tr>
<tr>
<td>IEEE Power Electronics Society</td>
<td>Advisor</td>
<td>Google’s official partner for the Google Little Box Challenge</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

## Workshops/Webinars/Public Demos

<table>
<thead>
<tr>
<th>Title</th>
<th>Location</th>
<th>Date</th>
<th># of Attendees</th>
</tr>
</thead>
</table>
## Media Coverage

<table>
<thead>
<tr>
<th>Media Outlet</th>
<th>Title</th>
<th>Date</th>
<th>URL</th>
</tr>
</thead>
<tbody>
<tr>
<td>ThinkProgress</td>
<td>If You Can Make Solar Power Better, Google Will Give You $1 Million</td>
<td>July 25, 2014</td>
<td><a href="https://thinkprogress.org/if-you-can-make-solar-power-better-google-will-give-you-1-million-40dd7a469786/">https://thinkprogress.org/if-you-can-make-solar-power-better-google-will-give-you-1-million-40dd7a469786/</a></td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th>Partner Name</th>
<th>Partnership Type</th>
<th>Description of Partnership</th>
<th>Partner Investment ($) (If Applicable)</th>
<th>Partner Value Add (In-Kind Commitment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sun Power Corporation</td>
<td>CRADA</td>
<td>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</td>
<td>$212,500</td>
<td>$30,000</td>
</tr>
</tbody>
</table>

### Software, Data Sets, or Hardware Developed

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
<th>Version</th>
<th>Date</th>
<th>Additional Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery Lifetime Prediction Model</td>
<td>Model for predicting the lifetime of a lithium-ion battery system given its configuration and operation profile</td>
<td>1.0</td>
<td>June 2016</td>
<td>Described in conference paper “Life Prediction Model for Grid—Connected Li-ion Battery Energy Storage System,” <a href="http://ieeexplore.ieee.org/abstract/document/7963578/">http://ieeexplore.ieee.org/abstract/document/7963578/</a></td>
</tr>
<tr>
<td>Residential Load Modeling Framework</td>
<td>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.</td>
<td>1.0</td>
<td>June 2016</td>
<td>Described in conference paper “Data-Driven Residential Load Modeling and Validation in GridLAB-D”, <a href="http://ieeexplore.ieee.org/abstract/document/7923933/">http://ieeexplore.ieee.org/abstract/document/7923933/</a></td>
</tr>
</tbody>
</table>
Appendix F. Additional Impacts and Outreach: Southern California Gas Company

Spin-Off Projects

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

Media Coverage

• “Are Ancient Bugs the Key to Storing Wind and Solar?” Stephen Lacey, Greentech Media podcast, October 15, 2019.

Workshops/Webinars/Public Demos
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.