



UNIVERSITY  
of HAWAII®  
SYSTEM

David Lassner  
President

DEPT. COMM. NO. 246

December 23, 2020

The Honorable Ronald D. Kouchi,  
President and Members of the Senate  
Thirty-First State Legislature  
Honolulu, Hawai'i 96813

The Honorable Scott Saiki, Speaker  
and Members of the House of Representatives  
Thirty-First State Legislature  
Honolulu, Hawai'i 96813

Dear President Kouchi, Speaker Saiki, and Members of the Legislature:

For your information and consideration, the University of Hawai'i is transmitting one copy of the Annual Report from the Hawai'i Natural Energy Institute (Section 304A-1891, Hawai'i Revised Statutes) as requested by the Legislature.

In accordance with Section 93-16, Hawai'i Revised Statutes, this report may be viewed electronically at: <http://www.hawaii.edu/offices/government-relations/2021-legislative-reports/>.

Should you have any questions about this report, please do not hesitate to contact Stephanie Kim at 956-4250, or via e-mail at [scskim@hawaii.edu](mailto:scskim@hawaii.edu).

Sincerely,

A handwritten signature in black ink that reads "David Lassner".

David Lassner  
President

Enclosure

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# UNIVERSITY OF HAWAI‘I SYSTEM ANNUAL REPORT



REPORT TO THE 2021 LEGISLATURE

Annual Report from the  
Hawai'i Natural Energy Institute

HRS 304A-1891

December 2020

# Hawai'i Natural Energy Institute

School of Ocean and Earth Science and Technology

University of Hawai'i at Mānoa

Annual Report to the 2021 Legislature

HRS 304A-1891



Annual Report on Activities, Expenditures, Contracts Developed, Advances in Technologies, Work in Coordination with State Agencies and Programs, and Recommendations for Proposed Legislation, required in accordance with HRS 304A-1891 (Act 253, SLH 2007).

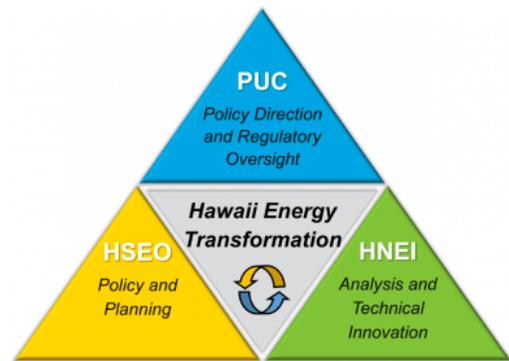
## **1. INTRODUCTION**

The Hawai'i Natural Energy Institute (HNEI) was created in 1974 to facilitate the development of the state's natural energy resources and reduce fossil fuel use in Hawai'i. Early efforts included resource assessments, demonstration projects, and research and development in the areas of alternative fuels, bioenergy, solar, and geothermal systems. In the early 2000's, HNEI took a growing leadership position in the development of public-private partnerships to accelerate the acceptance and integration of renewable energy technologies into Hawai'i's energy mix. HNEI emerged as a leader for sustainable energy development and the deployment and demonstration of emerging energy technologies.

In 2007, the Hawai'i Legislature (Act 253) established HNEI in state law with an expanded mandate to coordinate with state and federal agencies to demonstrate and deploy renewable energy, energy efficiency, and peak demand reduction technologies. Act 253 (2007) also established the Energy Systems Development Special Fund (ESDSF) and directed that it be managed by HNEI. Three years later, in 2010, Act 73 authorized 10 cents of the \$1.05 tax imposed on each barrel of petroleum product imported into Hawai'i be deposited into the ESDSF. These funds are intended to match funds from federal and

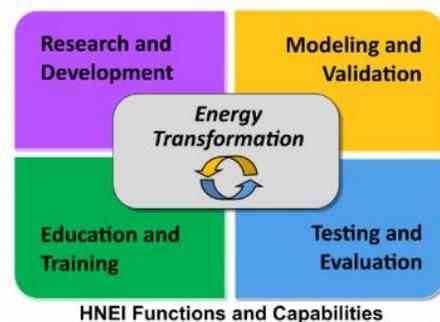
private sources, and to award contracts or grants for developing and deploying renewable energy technologies. (HRS Secs. 304A-1891-1894 and Sec. 304A-2169.1).

Hawai'i's energy transformation is driven by bold state policies that include a mandate for 100% renewable electricity and carbon neutrality by 2045. (HRS Secs. 269-92 & 225P-5). HNEI's responsibilities go beyond traditional academic research. A core part of HNEI's mission is to support Hawai'i in its clean energy transformation by focusing on cost effective and practical solutions to help deliver commercially viable renewable energy for the state and its citizens. HNEI robustly supports analysis to inform energy policy and decision making in Hawai'i. HNEI serves as a critical bridge between State and Federal initiatives in supporting the State's 100% renewable portfolio standard and clean transportation initiatives. HNEI is recognized as an independent organization providing trustworthy and practical information to support safe, reliable economic development of renewable energy systems and technologies.



The foundation of HNEI's strength lies in its people and its partners. The diversity of talents, education, experience, and entrepreneurial spirit of this team creates flexibility in performing a range of renewable energy development and analysis activities. HNEI brings together experts from a broad set of disciplines and organizations to develop solutions that will significantly impact energy transformation initiatives in Hawai'i and beyond. HNEI coordinates closely with the State Energy Office (formerly with the State Energy Coordinator), the Hawai'i Public Utilities Commission (PUC), utility, and industrial entities to maximize the value of state funds to meet needs and opportunities within the state, and to maximize matching funds from federal and private sources. HNEI also has strong working relationships with the members of Hawai'i's Congressional delegation and other government and non-government organizations in the Asia-Pacific region. By engaging in a wide range of disciplines and stakeholders, HNEI is able to tackle urgent and complex clean energy needs of our State, the nation, and partners in the Pacific region.

To accomplish this mission, HNEI integrates analysis, research, engineering, economics, and science to develop and demonstrate technologies, strategies, and policies that will significantly impact energy transformation initiatives in Hawai'i and beyond.



## **2. STAFFING/FUNDING OVERVIEW**

As an Organized Research Unit in the School of Ocean and Earth Science and Technology at the University of Hawai'i at Mānoa (UH), HNEI receives state funding via Hawai'i General Fund through the university budget sufficient to support its Director (Richard Rocheleau), three administrative support staff and partial salaries (60% to 80%) of seven additional tenure or tenure-track faculty (permanent faculty). The UH budget to HNEI also includes a small amount of tuition return.

HNEI has, over the past decade, consistently captured significant extramural funding, approximately \$10 million per year. HNEI's primary extramural support comes from the Office of Naval Research (ONR), the U.S. Department of Energy, and Naval Facilities Engineering Command, with smaller awards from industry and other government agencies such as the U.S. Department of Interior, the Army Research Office, and the Federal Aviation Agency. In addition, approximately 25% of the indirect funding generated by extramural awards are returned to HNEI to facilitate operations and research. Many of the projects funded by these entities use Hawai'i as a test site for alternative energy testing in the Pacific region, directly and indirectly supporting Hawai'i's clean energy goals.

In addition to supporting the balance of HNEI's permanent faculty, these funding sources support temporary faculty (approx. 20), temporary staff including engineers, scientists, and support personnel (approx. 16), as well as post-doctoral fellows, students, and visiting scientists (approx. 10 at any time) within HNEI; as well as faculty, students, and post-doctoral fellows in other departments and colleges.

HNEI also administers the Energy Systems Development Special Fund (ESDSF), allocated from the environmental response, energy, and food security tax ("Barrel Tax") pursuant to HRS Section 243-3.5. The ESDSF is used to leverage funding from federal and private sources; to develop and deploy technologies to reduce Hawai'i's dependence on fossil fuels; and to conduct analysis (often in support of the PUC) that directly supports Hawai'i's transition to a clean energy economy. As documented in Appendices A through I, efforts under ESDSF include in-house work, often as cost-share that leverages other federal dollars; and contracts with other organizations and consultants with specialized skills where in-house experience or availability is limited.

Generally, HNEI does not initiate legislation but, as evidenced by the project summaries Appendix A and Appendix B, HNEI projects do inform legislators and other Hawai'i government organizations with unbiased information and analysis on matters relevant to pending issues, bills, and proposals where appropriate. For example, HNEI provides a range

of support to the PUC including detailed analytic studies for evaluation of utility proposals. HNEI also supports and is a member of the Hawai'i Energy Policy Forum a collaborative energy planning and policy group comprising approximately 40 representatives from business, academia, government, and non-profit organizations focused on information sharing and education.

Staffing and expenditures for 2020 are summarized in the two tables below.

STAFFING	Director:	Richard E. Rocheleau
	Permanent Faculty (FTE)	7
	Other permanent staff (APT)	3
	Temporary Faculty	20
	Other temporary staff (APT, RCUH)	16
	Training (a)	10

(a) Includes post-doctoral fellows, graduate and undergraduate students, and visiting scientists.

EXPENDITURES:	General Funds \$ 1,385,500
	Tuition and Fees S Funds \$ 24,598
	Research and Training Revolving \$ 498,015
	Extramural Awards \$ 9,767,691
	Energy Systems Development Special Fund \$ 1,427,694

### **3. RESEARCH SUMMARIES**

Extramural funds garnered by HNEI support programs across a broad range of technologies and end uses including Energy Analysis and Policy, Grid Technology Development, Alternative Fuels including hydrogen, biofuels, and sustainable aviation, Electrochemical Power Systems including fuel cells and battery technology, Advanced Materials, Energy Efficiency, Transportation, Ocean Energy, and an active and rapidly growing International presence.

Within these areas, HNEI conducts or provides leadership for over 60 discrete projects. The various activities and key accomplishments under each of these projects are summarized in a series of one-page summaries called “Research Highlights” that are included within the nine Appendices of this report. These Research Highlights provide a brief and concise description of active HNEI research projects in an easily accessible format. Many contain links to more detailed reports, papers, and descriptions of HNEI’s work activities that are also available on its website ([www.hnei.hawaii.edu](http://www.hnei.hawaii.edu)). Sources of funding for each of the projects are also identified within the summaries.

Brief summaries of what is included in each of the Appendices follows.

#### **Appendix A: Hawai'i Energy Analysis and Policy**

Prior to 2018, grid analysis for Hawai'i was focused almost entirely on the evaluation of scenarios to manage curtailment when significant amounts of variable renewable generation were integrated into the grid. This work included a number of studies involving both on-island and off-island wind and solar as well as one-way and two-way transmission between the islands. The focus of renewable energy development in Hawai'i changed significantly when, in January 2019, the Hawai'i an Electric Company (HECO) received regulatory permission for seven solar-plus-storage projects comprising over 250 MW of solar and more than one GWh of storage. These projects for ‘dispatchable variable renewable’ generation were the result of the significant reduction in the cost of grid-scale energy storage.

In early 2020, HECO then selected an additional 16 projects totaling 460 MW of solar and an additional 3 GWh of storage for development. With these additions to their grids, the state of Hawai'i and HECO moved to the national forefront of tackling problems associated with high percentages of variable renewable generation.

Figure 1 shows the expected production of electricity by resource for the three HECO company systems assuming full buildout of the Stage 2 systems. The geographic isolation of the islands' electricity grids and lack of interconnection between islands makes Hawai'i's challenges of variable renewable integration more pronounced relative to mainland experience. Reliability issues are also exacerbated by relatively few, large generating units that make up the thermal generation component of the energy mix.

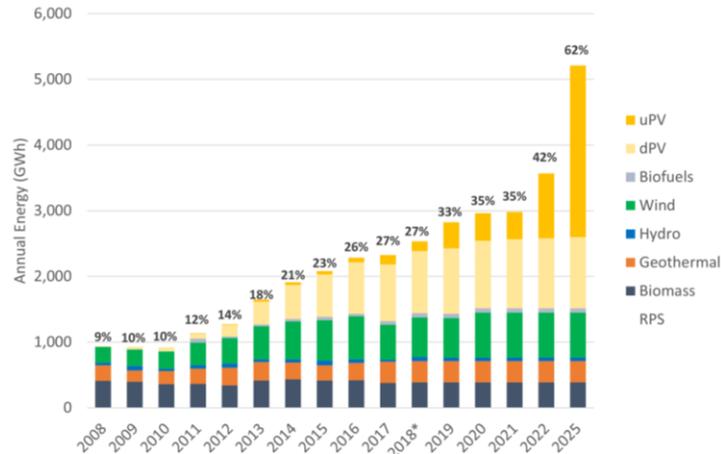


Figure 1

HNEI and its primary partner in these efforts, Telos Energy, have been actively engaged in developing tools and conducting analyses to better understand the impacts of this significant change to grid operations in Hawai'i. These efforts have included development of new tools to address the stochastic variability of the solar resource (Appendices A1 and A2), specific analysis to address the legislatively-mandated 2022 retirement of the AES coal plant on O'ahu (Appendices A3 and A4), and other analyses of the impact of even higher amounts of solar + storage on the grids (Appendices A5 and A6).

In addition to the technical analysis summarized in Appendices A1-A6, HNEI continues to work with the State Energy Office and the Hawai'i Public Utilities Commission to support state energy policy and Hawai'i's energy transformation. These activities include supporting analyses for the PUC, support of the utilities Integrated Grid Planning Efforts and ongoing support of the Hawai'i Energy Policy Forum based on the UH Mānoa Campus. These latter activities are summarized in Appendices A7 through A10.

### **Appendix B: Grid Technology Development**

With its very high penetration of distributed rooftop solar and the pending utility scale solar + storage projects, Hawai'i is at the forefront of tackling the problem of renewable energy integration. The geographic isolation of the islands' electricity grids and the exponential growth of renewable generation make Hawai'i's electricity grids particularly susceptible to the effects of intermittent and variable renewable energy sources, but also an ideal test bed for energy solutions. HNEI's portfolio includes a wide range of grid technology development efforts, ranging from development of new devices and methodologies to deployment and assessment of emerging technologies to better understand their value.

Appendices B1 through B3 summarize three grid-scale energy storage and energy management projects that have been deployed to evaluate the performance of energy storage and dynamic load banks to provide key grid services. Work described in Appendices B4 and B5 focuses on development of novel patent pending instrumentation for real time grid control. Several microgrid projects are summarized in Appendices B6 through B8, while Appendices B9 through B11 describe projects intended to demonstrate various energy conservation methodologies. Finally, Appendix B12 describes an effort to apply this knowledge to support Marine Corps Base Hawai'i's efforts to meet U.S. Department of Defense energy resilience requirements.

### **Appendix C: Alternative Fuels**

Alternative fuels, for both transportation and power generation, are an important component of Hawai'i's efforts to reduce its dependence on imported petroleum. HNEI conducts research, testing, and evaluation that supports the development of alternative fuels including biomass and biofuels, hydrogen and solar fuels, and methane hydrates. Projects range from development of new fuels characterization techniques to new methods for fuels production, and to exploration of potential future resources for fuels development. Appendix C1 describes a multi-university collaboration for development of sustainable aviation fuel. Appendices C2 through C5 describe technology development efforts for the production and characterization of alternative fuels. Appendices C6 and C7 summarize recently completed work on the properties of methane hydrates, a potential source of gaseous fuel, but which could also be a significant environmental risk.

### **Appendix D: Electrochemical Power Systems**

For almost two decades, HNEI has been conducting research, development, and testing of fuel cell and battery technologies. The primary goal of these efforts has been to understand the performance and durability of these electrochemical technologies for both commercial and military applications, including fuel cell powered and electric vehicles, fuel cell powered unmanned aerial and undersea vehicles, and, most recently, for grid services. Activities described in Appendices D1 and D2 focus on improved performance of proton-exchange fuel cells. Appendices D3 through D5 focus on development and characterization of platinum-free anion exchange fuel cells and new families of catalysts. Appendices D6 through D10 address projects to develop methodologies and understanding of the mechanisms affecting the lifetime of Li-ion and vanadium redox flow batteries.

**Appendix E: Advanced Materials**

The seven projects included in the Advanced Materials group, include development of novel techniques for the production of low cost photovoltaics (Appendix E1), development and testing of filtration materials and methodologies for fuel cell and other energy applications (Appendices E2 and E3), the production of high value products from biomass (Appendix E4), and three separate efforts to develop low cost, high performance hydrogen storage technologies (Appendices E5 through E7).

**Appendix F: Energy Efficiency**

The six projects included in the HNEI energy efficiency portfolio all have near-term value to Hawai'i. These include environmental monitoring of the potential outflow location for Honolulu Seawater Air Conditioning project (Appendix F1) which is intended to reduce future permitting costs. The remaining five projects are related to building efficiency. Appendices F2 and F3 summarize projects intended to facilitate improved building efficiency in Hawai'i's transit-oriented development areas and to inform Hawaiian Home Lands of best practices. Two projects (Appendices F4 and F5) address optimal operation of mixed-mode (natural and mechanical) ventilation in subtropical environments and development of advanced lighting controls for improved efficiency and security. HNEI also continues to host a Thermal Comfort Website for Hawai'i Department of Education (Appendix F6), providing open source information for developers interested in solutions for Hawai'i's educational facilities.

**Appendix G: Transportation**

In the area of transportation, HNEI has developed a state-of-the-art hydrogen fueling infrastructure on the Big Island (Appendix G1). This work is conducted in collaboration with the Natural Energy Laboratory Hawai'i Authority (NELHA), the County of Hawai'i, and the Hawai'i Island Mass Transit Agency (Hele-on bus). Appendix G2 describes a demonstration of two-way EV charging intended to develop advanced controls optimizing grid services and vehicle use.

**Appendix H: Ocean Energy**

Since 2015, HNEI has been engaged in a cooperative effort between the U.S. Navy and U.S. Department of Energy to support testing of pre-commercial wave energy conversion devices in a real-world operational setting offshore from Marine Corps Base Hawai'i. Appendix H1 summarizes progress to date and future plans for this site. More recently, HNEI has received an award from the U.S. Department of Energy to develop its own wave energy technology. Only recently initiated, a description of the technology and development plans are summarized in Appendix H2.

**Appendix I: International Support**

In 2017, HNEI was the recipient of a multimillion-dollar award from the Office of Naval Research titled “Asia-Pacific Regional Energy Systems Assessment (APRESA),” intended to facilitate development of clean, resilient, efficient energy systems throughout the Asia-Pacific region. Appendix I1 describes a number of projects under this award, including ones in Vietnam, Thailand, Indonesia, Cambodia, and the Philippines. Appendices I2 and I3 provide additional detail on two of these projects, a collaboration with the Energy Generation Authority of Thailand and a mapping of the renewable energy innovation sector in Vietnam. These efforts under APRESA have resulted in a close relationship with U.S. Agency for International Development (USAID) and various USAID contractors. Appendices I4 through I6 summarize other projects, including a feasibility study for use of energy storage to mitigate transmission constraints in Vietnam, an Artificial Intelligence (AI) based microgrid project at NELHA funded by the Korea Institute of Energy Technology, Evaluation and Planning, and a U.S. India collaborative for development of smart grid technologies.

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# Hawai'i Natural Energy Institute Research Highlights

## Appendix A: Hawai'i Energy Policy and Analysis

### A1: Stochastic Modeling for High Renewable Grids

**OBJECTIVE AND SIGNIFICANCE:** As the amount solar and storage integration increases in Hawai'i, accurately capturing the impact of weather variability and uncertainty is critical. In addition, with the relatively small number of generating units on Hawai'i's grid, correlated outages and maintenance events can significantly decrease reliability. The objective of this work conducted by HNEI in collaboration with Telos Energy was to develop novel methodologies and tools to properly evaluate system risk and the likelihood of capacity shortfalls in high percentage renewable grids by probabilistically simulating solar variability, generator outages, and storage availability.

**KEY RESULTS:** A novel methodology to capture the impact of solar variability, generator outage, and storage availability on the reliability of high percentage renewable grids was developed. A 21-year dataset of solar irradiance and production profiles as well as detailed probability distributions of generator outages and maintenance schedules were developed to allow application of this methodology to the Hawai'i grids. The methodology captures inherent solar variability, outlier weather events, and the impact of generator outages. This new analysis technique helps answer key questions for power system planning that are missed by traditional resource adequacy analysis such as:

- How much solar, storage, and thermal capacity is required to maintain grid reliability?
- What is the effect of increased forced outages and maintenance schedules on reliability?
- How much legacy thermal capacity can be retired?
- How do multi-day low solar and extreme weather events affect reliability?

**BACKGROUND:** Historically, production cost analyses used to model economic dispatch of utility generation sources typically focus on modeling hour-to-hour and sub-hourly solar variability across a single weather year. As battery storage is deployed in quantities that impact grid operations, the challenge of sub-hourly variability of the solar resource becomes less important. Instead, periods of challenging operations due to extended periods of low solar output may occur. When these challenging periods of low solar resources are concurrent with

generator failures, unserved energy may result. This occurs when there is not enough capacity to serve load. This issue may be particularly acute for Hawai'i's grids, which have relatively few, large generators relative to the size of the load. This risk to system reliability is expected to become more serious as Hawai'i's fossil fleet ages as more frequent outages and maintenance events, increasing the likelihood of concurrent events.

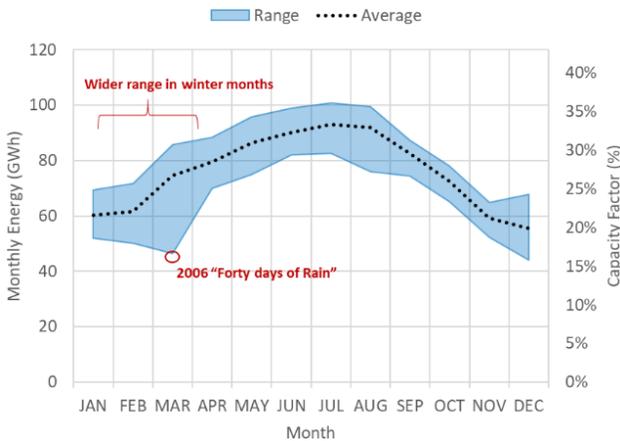
Traditional power system planning evaluates weather risk and generator outages via resource adequacy analysis rather than hourly production cost analysis. This traditional resource adequacy analysis leverages stochastic, probabilistic assessments of risk (weather and generator outages), to determine the likelihood of capacity shortfalls. However, this analysis is limited because it does not capture chronological dispatch of the power grid, but instead evaluates snapshots in time, such as peak load hours. This inability to capture chronological dispatch is likely to miss significant events when evaluating systems with high levels of energy limited resources, such as battery storage and demand response.

The increasing importance of weather uncertainty and generator outages, combined with the need to accurately simulate storage and demand response, requires novel methodologies and tools to properly evaluate system risk and the likelihood of capacity shortfalls. Under this activity, a new model to capture the stochastic nature of grids with a high penetration of variable renewable generation has been developed and used to analyze capacity reliability of the Hawai'i grids.

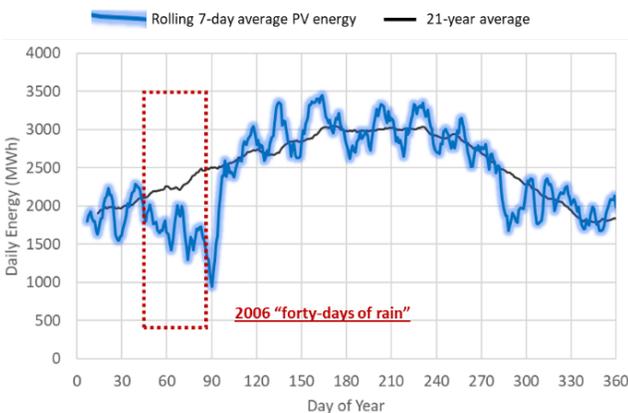
**PROJECT STATUS/RESULTS:** To address the evolving challenges of system reliability on the Hawai'i grids at high levels of solar and storage integration, HNEI and Telos Energy developed and applied novel grid modeling techniques and tools to stochastically evaluate system operation across many years of historical weather data and potential generator outages. The project includes the development of a detailed, Hawai'i-specific, historical weather database. Weather conditions were simulated over the past 21 years using National Renewable Energy Laboratory's (NREL) National Solar Radiation Database (NSRDB). Combining the weather data with solar PV plant-specific

information, such as location, DC:AC ratios, tracking systems, etc., resulted in unique sub-hourly power production profiles for each existing and proposed solar PV project in Hawai'i. The figure below illustrates the system-wide variability in monthly generation (top) and an example of a single year's rolling weekly average of solar generation relative to the 21-year average (bottom).

**Monthly Solar Variability Across 21-years**



**2006 Solar Year vs. 21-year Average**



The methodology incorporates the historical weather data for chronological solar production profiles and then simulates grid performance for those years against a series of randomly selected generator outages and maintenance events. In the analysis conducted to date, 21 years of historical solar data and up to twelve random outage profiles were used resulting in a matrix of 252 Monte Carlo samples, each analyzing a full 8,760 hour year of chronological operation. The result is the probability of a capacity shortfall across nearly 2.5 million hours of grid operation.



This process allows for the calculation of conventional resource adequacy metrics, like Loss of Load Expectation (LOLE), Loss of Load Hours (LOLH), and Expected Unserved Energy (EUE), along with typical production cost metrics like cost of generation and curtailment. It also accurately captures battery utilization and state-of-charge as well as better incorporating storage scheduling, which inherently increases capacity margins in some hours (charging) in order to reduce risk in others (discharging).

In addition to the traditional resource adequacy metrics like LOLE and LOLH that only characterize the frequency of capacity shortfalls, the stochastic analysis developed under this project provides additional information, such as the size and duration of events. This ability to characterize size, frequency, and duration of reliability events offers the opportunity to tailor mitigations to meet grid needs. This allows for a more effective comparison between mitigation technologies and operational responses, such as battery energy storage, demand response, and fossil capacity additions for reliability. For example, battery energy storage and demand response may be preferred options to mitigate short duration events, whereas fossil generation or long-duration storage will be required for longer duration events.

**Loss of Load Hours by Replication**

Solar Year	Outage Draws											
	1	2	3	4	5	6	7	8	9	10	11	12
1998	0	0	5	0	0	0	0	0	0	2	0	3
1999	0	0	6	0	0	0	0	0	2	0	18	0
2000	0	0	0	2	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	2	0	0	0	1
2003	0	2	3	0	0	3	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	1	0	0	0	0	0
2006	0	0	0	0	0	0	2	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	4	0	0	0
2010	0	0	0	0	0	0	0	0	0	0	0	0
2011	3	0	0	0	0	0	0	0	1	0	0	0
2012	0	0	0	0	0	0	0	0	0	0	0	0
2013	0	0	1	0	0	2	2	0	0	0	0	11
2014	0	0	1	0	0	0	0	3	0	0	0	0
2015	0	0	0	0	0	0	3	0	0	0	1	0
2016	0	0	0	0	0	0	3	0	0	0	0	3
2017	0	0	0	0	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	1	0	0	0	0

The new modeling techniques and tools outlined in this report were developed to allow more accurate and higher fidelity analysis of the need for capacity and risks of unserved energy as the Hawai'i grids transition to increasing levels of solar and battery storage. This tool is being used to evaluate issues, such as the reliable retirement of fossil generators, the value of demand response, and battery storage for capacity grid services, as well as the role of long-duration storage for future power systems. These topics are covered in separate reports in this section.

*Funding Source:* Office of Naval Research; Energy Systems Development Special Fund

*Contact:* Richard Rocheleau, [rochelea@hawaii.edu](mailto:rochelea@hawaii.edu)

*Last Updated:* November 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix A: Hawai'i Energy Policy and Analysis A2: Integrated Stability and Cost Production Analysis

**OBJECTIVE AND SIGNIFICANCE:** As the Hawai'i grids transition to high penetrations of solar plus storage to meet generation needs, conventional stability tools that utilize a limited number of snapshots of operations expected to show worst-case conditions (i.e. an evening peak load) cannot capture the range of grid conditions that are important to evaluate on high percentage-renewable grids.

The objective of this activity, conducted in collaboration with Telos Energy, was to develop a new tool to evaluate grid stability over the entire range of operations expected throughout the course of a year. Evaluating grid risk at every hour of the year enables grid planners to understand both the magnitude and duration of risk to the grid, which gives valuable context for informing mitigation decisions. A second objective of this activity was to integrate both stability and cost production into one tool, with a significant improvement over traditional tools that cannot co-optimize production cost and grid stability.

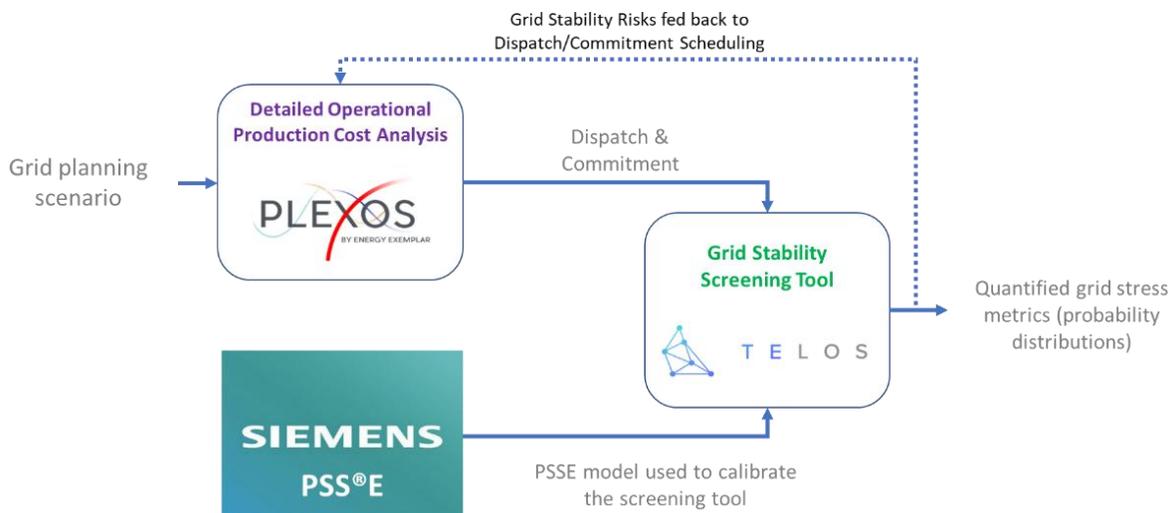
**KEY RESULTS:** The HNEI team has successfully developed a new screening tool that quantifies the stability risk to the grid using a probabilistic approach across all 8760 hours of grid operation instead of just at preselected conditions of expected risk. This technique yields probability distributions of the frequency excursions for grid events such as loss-of-generation. This new tool provides a more comprehensive means for assessing stability of the Hawai'i grids as conventional thermal generation is retired and replaced by variable renewables systems.

The accuracy of this new tool was calibrated using the full dynamic model of the O'ahu grid and validated against the typical transmission planning snapshots as described below.

**BACKGROUND:** Typical utility grid planning processes only evaluate a limited number of grid conditions for dynamic stability, sometimes as few as two or three "worst-case" snapshots (i.e. summer peak, spring light-load conditions) from each planning scenario. This traditional approach provides limited information for today's modern grids with high penetrations of variable renewable resources and storage because (1) the "worst-case" periods are shifting and no longer obvious and (2) this approach provides no indication of how often the grid is exposed to the "worst-case" conditions, which is critical in understand how to best mitigate issues that arise.

To overcome these limitations, the HNEI team developed and validated a new tool to evaluate the stability and performance of the grid probabilistically across all 8760 hours of the study year for each scenario. This enables a comprehensive, yet easy-to-understand view of how system risk changes as the grid evolves.

**PROJECT STATUS/RESULTS:** The new tool enables an analysis that is both broad and deep by combining the wide range of realistic grid operating conditions over the course of an entire year (from PLEXOS) with the detailed dynamic behavior of the grid during major grid events (from PSSE). The core of the tool



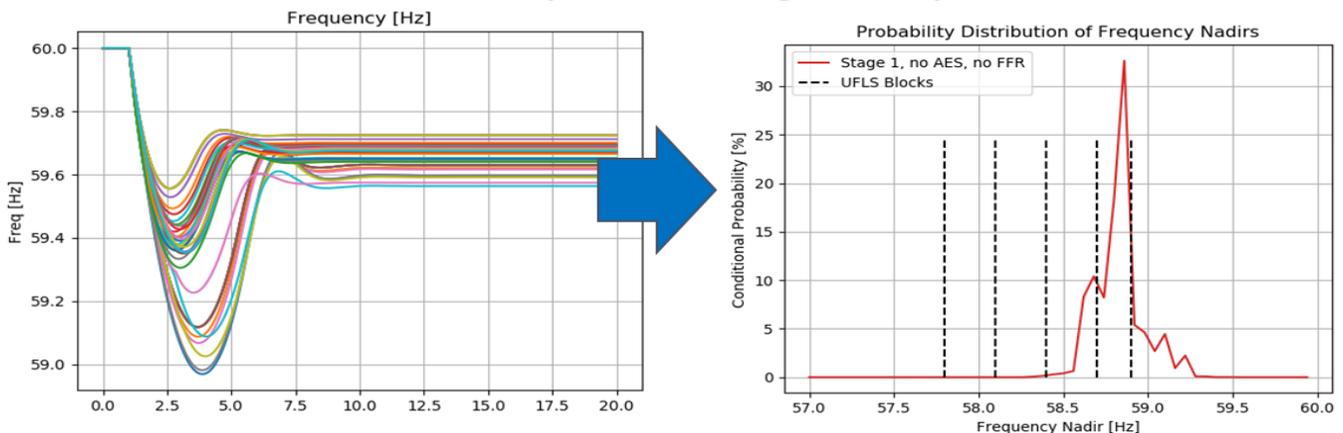
is a simplified dynamic model of the island power system. This simplified model is then calibrated using the detailed dynamic model from PSSE. This calibrated, grid-specific model then uses inputs from the production cost tool (PLEXOS), such as the total thermal generation online, renewable generation, and energy storage reserves to estimate the grid frequency excursion for each hour of the simulation assuming loss of the largest single generator on the grid. This methodology is shown schematically in the figure on the previous page.

The output of the tool, the frequency nadir, is captured to show the stress on the grid and the impact to customers. The frequency nadir is the minimum frequency that is reached after the loss of generation event. Lower values of frequency nadir indicate higher levels of grid stress and greater likelihood of a blackout or the need for load shedding or blackout. To quantify customer impact, the probability of load disconnection due to the under-frequency load-shedding scheme on the grid is reported. To more easily visualize these results, the frequency nadir and load-shedding metrics are presented as probability distributions that show the probability of reaching a certain level of grid stress (frequency nadir and load-shedding) over the course of a year for a given mix of generation resources. This is shown in the figure below, where the frequency nadir from 8,760 individual dynamic simulations can be represented as a single probability distribution curve. By running multiple future resource mixes that consider different penetrations of solar + storage, the probability distributions can be plotted to show the trends in dynamic stability as the grid becomes increasingly renewable.

As indicated in the schematic, this new tool is fully integrated with PLEXOS allowing the results of the dynamic stability simulations to be fed back to PLEXOS, where the scenarios and/or the grid operations can be adjusted to achieve desired levels of grid stability, such as a maximum value of load-shedding or a minimum allowable frequency nadir. This is fundamentally different than traditional techniques where system cost is optimized first without regard to stability, then adjustments to the grid that are needed for grid stability reasons are made second, which leads to a suboptimal resource mix. Based on the desired stability objectives, operational parameters such as generation commitment decisions, generation retirement and replacement scenarios, battery scheduling and utilization, and demand response assumptions can all be adjusted individually or in combination.

This tool has been applied to the Island of O‘ahu to assess grid stability with high solar + storage integration and evaluate the risk of customer disconnection and grid black-out for near-term scenarios including the retirement of AES and the installation of Stage 1 PV+BESS projects. The results are detailed in Appendix A4. The tool has been benchmarked against the full dynamic model of O‘ahu as represented in PSSE for four different grid conditions, including the maximum and minimum loads during daytime and nighttime periods (see figures on following page). In each case, the largest single generator is suddenly disconnected and the grid frequency is over-plotted. The focus of the validation is on matching the frequency nadir, which is considered the most important grid stress metric for

### An Improved Screening Tool Analysis



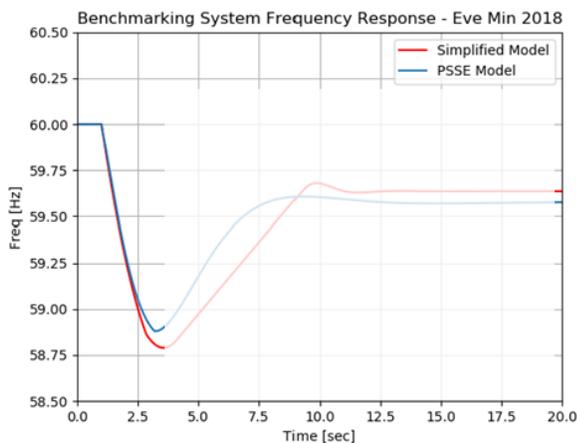
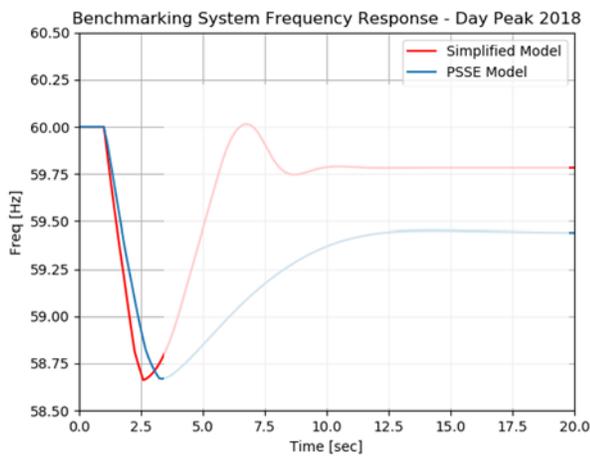
loss-of-generation events and directly corresponds with load-shedding on O‘ahu. It is acknowledged that the dynamic response of the grid predicted by the tool after the frequency nadir occurs is often not accurate. This is because the response of the grid after the nadir is dependent on many other dynamics (thermal generator governor dynamics) that are not modeled. These post-nadir dynamics are not modeled because they are not significant factors in the response of the grid prior to the nadir. It is the period of time prior to the nadir that is the focus of this analysis because this period is most critical for the survivability of the grid and most indicative of grid stress and customer impact.

method and analysis tool can be adapted to evaluate these risks as well, which is expected to be critically important for O‘ahu, Maui, and Hawai‘i in the near future.

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*Last Updated:* November 2020



The loss-of-generation events are only one type of challenging grid event that grid operators and planners must assess. Other challenging events including short-circuit (fault) events, particularly with low grid strength, which occurs when there are high levels of generation from inverter-based resources and few conventional plants online. This



# Hawai'i Natural Energy Institute Research Highlights

## Appendix A: Hawai'i Energy Policy and Analysis

### A3: Grid Reliability with AES Retirement

**OBJECTIVE AND SIGNIFICANCE:** The AES Hawai'i coal plant, the largest power plant on O'ahu is scheduled to retire in 2022. This retirement will decrease the amount of dispatchable fossil capacity available to the utility by more than 10%. The objective of this study was to evaluate the ability of proposed solar + storage resources to maintain grid reliability with the pending AES coal plant retirement. The results of this analysis are being briefed to the Hawai'i Public Utility Commission (PUC) and other stakeholders and are expected to have important implications for power system planning and policy for O'ahu.

**KEY RESULTS:** Stochastic analysis, using the tools developed by the HNEI-Telos Energy team (Appendix A1), that included the annual variability of the solar resource over 21 years and a variety of fossil plant outage profiles was conducted. It was determined that the AES retirement is likely to increase reliability risks, with increased likelihood of loss of load events (LOLE). This could occur even if Stage 1 solar + storage resources are fully deployed and would be considerably worse if there are delays in project commissioning. However, reliability is maintained or even improved once Stage 1 and a relatively small fraction of the Stage 2 solar + storage projects are completed. While standalone storage was found to effectively mitigate the reliability concerns, other potentially less costly solutions were also identified.

**BACKGROUND:** As the Hawai'i grid transitions to higher percentages of renewable energy, new resources are being integrated to not only provide renewable energy, but also to provide the grid services conventionally provided by AES and other fossil generation. Combining solar and battery storage resources allows solar energy to be shifted from the middle of the day when there is surplus renewable generation to evening peak load hours after the sun has set. This allows the dispatchable hybrid solar + storage projects to replace and retire conventional fossil generation such as the AES coal plant. The ability of the O'ahu grid to replace large amounts of energy currently supplied by thermal generation with energy supplied by solar + storage systems without significant curtailment is described in more detail in Appendix A5. The inclusion of storage into these systems offers the opportunity for

them to provide grid services, one of which is capacity – or the ability to provide energy when it is required for reliability. However, there are limitations that arise due to the reliance on the variable solar resource, energy limitations of the storage, contractual limitations for battery charging, and uncertainty of generator outages.

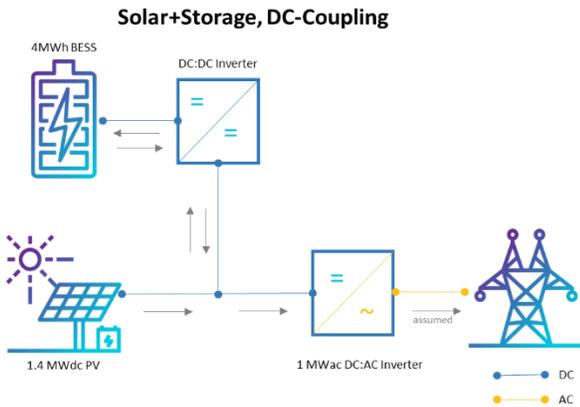
The AES coal plant is an independent power producer with a long-term Power Purchase Agreement (PPA) with Hawaiian Electric Company (HECO) that expires in 2022. HECO does not plan to renew the PPA. In addition, SB 2629 enacted in 2020 bans coal-fired generation in Hawai'i after 2022, ensuring the AES retirement. Given the relatively short timeframe, the most likely replacement resources are the announced Stage 1 solar + storage projects (137 MW of solar, 548 MWh of storage), potential standalone battery storage, and demand response.

The Stage 1 projects were originally proposed to be completed in 2022, concurrent with the AES retirement. However, as of October 2020, some of the projects are delayed between 6-13 months, potentially pushing out their availability to after the legislatively mandated AES coal retirement. An additional 287 MW of solar, 1,275 MWh of battery storage was awarded in the "Stage 2 RFP" that could also provide replacement capacity for the AES retirement, but most of these projects, as proposed are not expected to be online until 2023 or later. As a result, the timing of the AES retirement and replacement solar + storage projects could jeopardize system reliability in the short run.

To overcome this concern, HECO has awarded – also through the Stage 2 RFP – a PPA for the 185 MW battery energy storage project to be located in Kapolei. This project is being developed as a direct replacement for the AES capacity. However, given the amount of solar + storage resources going in through the Stage 1 and Stage 2 renewable procurements, there may be significant surplus of capacity available shortly after the AES retirement.

It is therefore important to understand the extent to which hybrid solar + storage resources can reliably replace fossil generation, while also considering the technical and contractual limitations of the resources. The Stage 1 projects consist of four solar + storage hybrid projects, totaling 137 MWac of capacity.

These hybrid projects are DC coupled, where the battery storage and solar PV share a common DC:AC inverter and grid connection (see figure below). As indicated in the figure, each of the Stage 1 projects has an overbuild of the PV panels of approximately 40% and includes 4 hours of storage relative to the nameplate rating of the plant. Energy generated by the plant can go directly onto the grid or via the battery, but the total output of the plants at any given time is limited to the AC rating of the plant.



In addition, contractual restrictions on the operation of the Stage 1 projects requires charging of the battery to come predominately from the solar resource, as opposed to the grid, for the first five years of the project. These restrictions intended to secure the maximum benefit from the federal investment tax credit have been included in the analysis.

As described in Appendix A1, novel modeling techniques were developed to accurately account for the chronological operations of storage, solar variability, and generator outages. This new stochastic methodology combines the disciplines of resource adequacy analysis with operational production cost modeling to better simulate grid reliability with high penetrations of solar, storage, and demand response. These methodologies have been applied to the O‘ahu grid to determine if solar + storage systems could maintain reliability when AES is retired.

**PROJECT STATUS/RESULTS:** The stochastic methodology previously described was used to evaluate the reliability of near-term changes on the O‘ahu grid, specifically the retirement of the AES coal plant and successive buildout of large amounts of utility-scale solar + storage resources. Six levels of solar + storage buildout, up to an additional 426

MWac of solar with 1,833 MWh of battery storage, representing the full buildout of recently awarded Stage 1 and Stage 2 projects were evaluated.

Each case was analyzed across 252 random draws (replications) of chronological dispatch, representing 21 years of solar data and 12 outage profiles. The output of the analysis included the number, the magnitude, and the duration of the capacity shortfall events that occur when there are not enough available resources to serve load. This methodology was repeated across eight cases, one of which represents the current system (Base Case), one with AES retired without any replacement capacity, and the six additional cases with AES retirements and incremental additions of solar + storage resources up to the equivalent capacity of the Stage 2 buildout.

The matrices on the following page summarize the number of hours of unserved energy for two of the eight cases, the Base Case, and a case assuming the AES retirement and full build out of the Stage 1 projects. For each case, the number of hours of unserved energy for each of the 252 random draws of solar and unit outages are shown. As the matrices below indicate, many draws do not have any capacity shortfall events, but on average, the number of hours with outages increases by 82% when AES is retired and only replaced with Stage 1 resources.

Interestingly, the results summarized in these matrices indicate that even with an increased reliance on solar-based resources, there is no clear dependence on which year of solar data is used. This suggests that, at this level of solar + storage integration, annual weather variability, and extreme weather events do not significantly affect system reliability. As discussed in more detail below, the results show that even in years that do have capacity shortfalls, the majority of outages are only between 1-4 hours durations.

In contrast to the lack of dependence on the solar year, a strong dependence on the outage draw is indicated. While the total amount of outages used as input to the analysis was consistent across the random draws, the timing and characteristic of the outages changes across the random samples. This is strong evidence that the timing and correlation of fossil generator outages is the primary cause of capacity shortfall events.

### Loss of Load Hours by Solar Years & Outage Draw

Solar Year	Outage Draws											
	1	2	3	4	5	6	7	8	9	10	11	12
1998	0	0	5	0	0	0	0	0	0	2	0	3
1999	0	0	6	0	0	0	0	0	2	0	18	0
2000	0	0	0	2	0	0	0	0	0	0	0	0
2001	0	0	0	0	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	2	0	0	0	1
2003	0	2	3	0	0	3	0	0	0	0	0	0
2004	0	0	0	0	0	0	0	0	0	0	0	0
2005	0	0	0	0	0	0	1	0	0	0	0	0
2006	0	0	0	0	0	0	2	0	0	0	0	0
2007	0	0	0	0	0	0	0	0	0	0	0	0
2008	0	0	0	0	0	0	0	0	0	0	0	0
2009	0	0	0	0	0	0	0	0	4	0	0	0
2010	0	0	0	0	0	0	0	0	0	0	0	0
2011	3	0	0	0	0	0	0	0	1	0	0	0
2012	0	0	0	0	0	0	0	0	0	0	0	0
2013	0	0	1	0	0	2	2	0	0	0	0	11
2014	0	0	1	0	0	0	3	0	0	0	0	0
2015	0	0	0	0	0	0	3	0	0	0	1	0
2016	0	0	0	0	0	0	3	0	0	0	0	3
2017	0	0	0	0	0	0	0	0	0	0	0	0
2018	0	0	0	0	0	0	0	1	0	0	0	0

**Base Case**

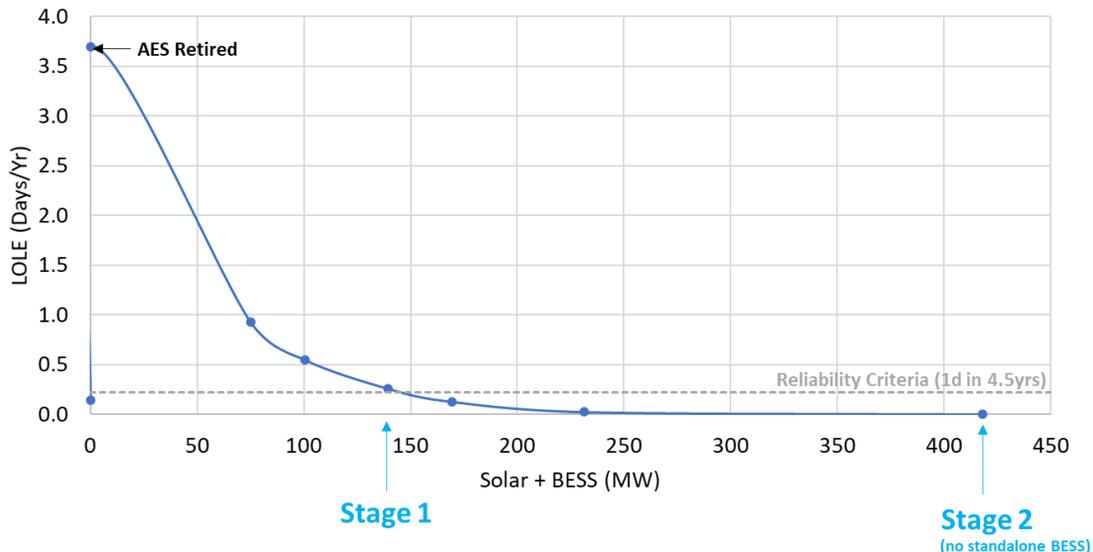
Solar Year	Outage Draws											
	1	2	3	4	5	6	7	8	9	10	11	12
1998	0	0	10	3	0	0	2	0	3	6	0	0
1999	2	0	9	0	3	0	0	0	0	0	3	0
2000	0	0	0	0	0	0	0	2	0	0	6	0
2001	0	0	0	2	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	6	0	0	0	0
2003	0	0	1	0	0	0	0	0	0	0	0	1
2004	0	2	0	0	0	1	0	0	0	0	0	0
2005	0	0	0	4	0	0	0	1	0	0	0	0
2006	0	0	0	0	0	0	0	0	0	0	3	0
2007	0	3	0	0	0	2	0	0	0	0	0	0
2008	3	0	0	0	0	0	0	5	0	0	0	0
2009	0	0	2	0	1	0	0	1	0	0	3	0
2010	0	0	0	0	0	0	0	0	0	0	0	0
2011	11	0	2	0	0	0	0	0	1	0	3	0
2012	0	3	0	0	0	0	0	0	0	0	0	0
2013	2	0	3	3	0	2	0	0	0	0	0	7
2014	0	0	10	0	0	0	0	0	0	0	0	0
2015	1	0	0	0	3	0	8	0	0	0	0	0
2016	0	1	0	2	0	0	0	0	1	0	0	0
2017	0	0	0	0	0	0	1	1	0	0	0	0
2018	0	10	0	0	0	0	0	0	0	0	0	1

**AES Retired + Stage 1**

For each case, the results of the 252 random draws are summarized into a single metric, the average LOLE value across all the draws. Additional metrics are quantified, including loss of load expectation (LOLE), which summarizes average days per year with a capacity shortfall event; loss of load hours (LOLH), which summarizes the average number of hours per year; and expected unserved energy (EUE), which provides an average amount of unserved energy (MWh) per year. The figure below shows the average LOLE for each of the eight cases. LOLE (y-axis) is plotted against increasing solar + storage adoption (x-axis). Low values represent lower risk of capacity shortfall. The dot on the lower left y-axis represents the Base Case, the current system before

the AES retirement and without additional solar + storage. The line represents system reliability after the AES retirement with increasing amounts of solar + storage.

It should be noted that while the LOLE metric provides a quantitative measure of system risk, the absolute number is very sensitive to changes in assumptions. Because the O‘ahu grid is a small system, changes to the underlying outage rates and planned outage schedules can significantly change the reliability metrics. It is therefore important to use consistent assumptions across the cases and evaluate the relative differences across cases rather than focus on the absolute level of reliability.



While the figure on the previous page highlights unacceptable reliability with the AES retirement without additional solar + storage, much of that loss of reliability is recovered with the installation of the Stage 1 solar + storage. The figure below with an expanded y-axis allows better comparison of the current system against the solar + storage replacement cases. As shown, relative to AES retirement without the addition of solar + storage, while much of the loss in reliability caused by the retirement of AES is recovered when the Stage 1 projects are included, the modeled reliability is still nearly twice that of the original baseline condition with AES operating. The chart also shows that partial deployment of the Stage 2 projects in addition to the Stage 1 is sufficient to bring the system back to the same level of reliability.

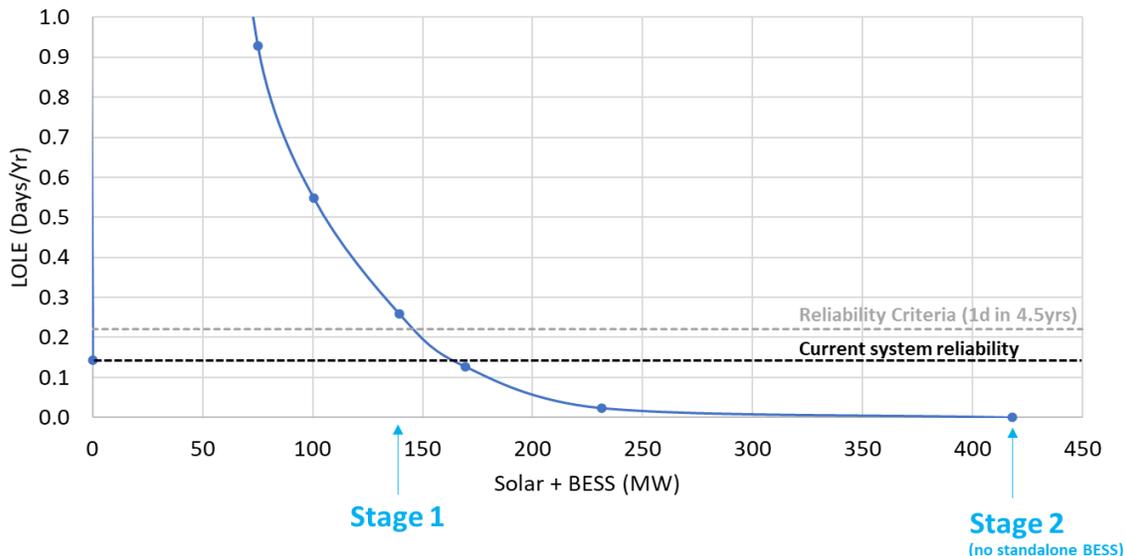
This finding is important. **It indicates that, with close to a one-to-one capacity swap, the hybrid solar + storage resources can be effective and reliable replacement resources for a coal fired generator.** While solar + storage resources can reliably replace baseload coal, the system will need more capacity than just the Stage 1 projects. The results show that 166 MW of solar + storage (13% more than Stage 1) is sufficient to replace 185 MW of fossil generation (8% less capacity). In this analysis, because solar + storage systems are highly modular, made up of many discrete components, the analysis assumed there is no failure mode likely to cause a major loss of production like a steam turbine generator that can lose 185 MW of capacity in a single outage. More investigation of potential transmission-

related outages is needed to determine if there is risk of single failure modes that could create an outage of a full solar + storage facility. The potential for solar + storage outage rates would increase the reliability risk and require even more capacity to replace AES.

In summary, with the addition of as little as 30% of the Stage 2 solar + storage projects, capacity shortfalls are eliminated altogether. This indicates that with Stage 2 implementation, there is sufficient surplus capacity available to the grid, negating the need for a standalone battery.

On the other hand, the results also indicate that project cancellations or delays in the Stage 1 projects would increase reliability risk, potentially significantly. For example, if 50 MW of projects are delayed, which represents only one of the Stage 1 projects, the projected probability of a capacity shortfall doubles. **This clearly shows the need for a mitigation plan to ensure project delays do not further erode reliability.**

Conventional resource adequacy metrics currently used by the utility are limited, typically reported only as the probability of a capacity shortfall event (LOLE). Additional information that characterizes the size, frequency, and duration of capacity shortfalls is important to ensure mitigations are right sized for the reliability needs of the system. This allows the use of energy limited resources like demand response and battery energy storage to provide key grid services. These additional metrics are accessible via the stochastic analysis used for this work.



The figure below provides a probability distribution for capacity shortfall durations for the Base Case and the full build out of the Stage 1 projects with AES retired. The figure on the left shows the probability of an outage of a specified duration while the figure on the right shows the cumulative probability function. These results show that nearly all events, with Stage 1 installed, are four hours or less, with more than half of all shortfall events limited to less than two hours. This means that a short duration energy storage or demand response resource, used sparingly, can effectively improve reliability, eliminating the need for additional fossil generation.

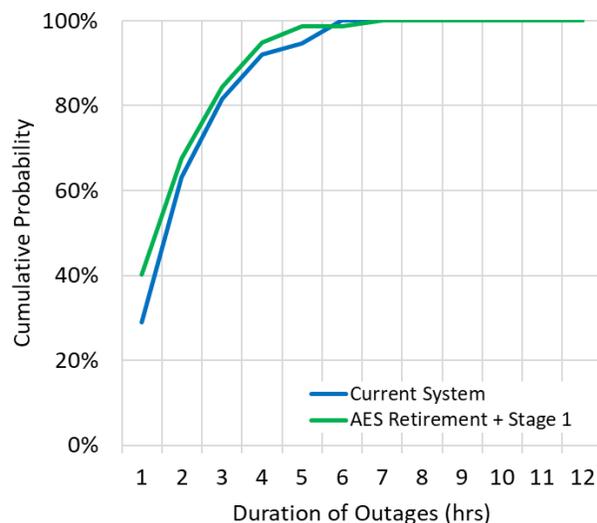
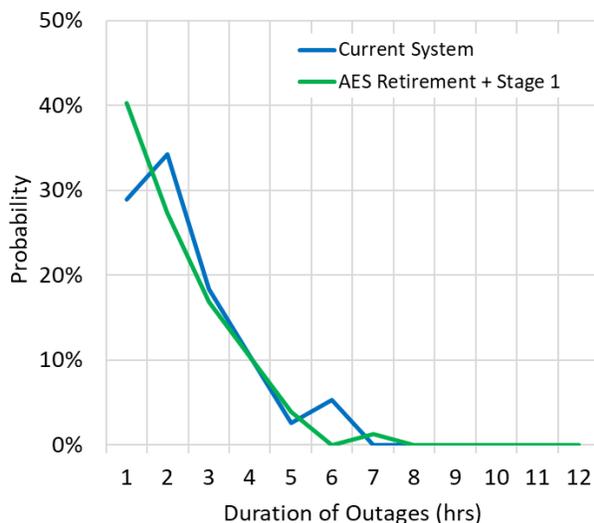
The ability of limited energy standalone batteries and demand response was evaluated to quantify their ability to mitigate these short duration reliability risks. A series of simulations were conducted adding incremental demand response and battery storage capacity to the system. This was done assuming 50% of Stage 1 projects were installed and again assuming full buildout of the Stage 1 solar + storage.

- **Standalone Storage:** The standalone storage was configured to represent the proposed Kapolei energy storage project, at 185 MW, 565 MWh (3-hour duration). A scaled down, 60 MW configuration, was also evaluated. Neither configuration was assumed to have restrictions on charging.
- **Demand Response:** Two types of demand response programs were evaluated. One program, which represents limited flexibility, evaluated 60 MW of demand response with 1-hour duration (60 MWh per day), a maximum

number of 40 calls per year, and could only be utilized on weekdays from 8am to 9pm. This is indicative of HECO’s current “Fast DR” program. A more flexible demand response option with energy duration to 2-hours (120 MWh), and no time of day restrictions was also evaluated.

Results of these cases indicate that even a modest amount of new resources can substantially improve reliability. With Stage 1 fully deployed, a 60 MW demand response or energy storage asset would make the grid twice as reliable as the current system. Even with only a 50% partial buildout of Stage 1, approximately 60 MW of battery or demand response would significantly improve reliability compared to the PV + storage alone, although more would be required to reach current reliability levels. **This finding is important, as it indicates that at current levels, solar + storage, demand response, and battery storage all provide approximately 1-for-1 replacement capacity for fossil generation and are roughly equivalent from a capacity perspective.** Across both cases, the addition of 185 MW of standalone storage is significantly more capacity than is required to meet reliability requirements.

However, it should be noted that the 1-for-1 equivalency of energy limited resources will not continue indefinitely. Saturation of these resources is likely and their ability to replace fossil will diminish at higher penetration levels of solar + storage. The capacity value of energy limited resources at very high penetration is evaluated further in Appendix A6.



These results show that these additional resources for reliability are rarely called on, indicating that a resource that is only available several days a year can yield significant reliability benefits (see left figure below).

One of the most important factors impacting reliability of a power system is the expected outage rates of the generating equipment. This is especially true for small, islanded power grids where concurrent outages of generators can have a large effect on reliability. This applies to both planned maintenance and unexpected failures (forced outages). O‘ahu’s installed capacity is 44 years old on average, with 260 MW of capacity over 60 years old. In addition, the older steam generator technology was not designed to cycle and ramp regularly in response to wind and solar variability.

In 2016 there was a significant increase in the maintenance and forced outage rates for the HECO fleet, which is presented in the figure on the right. While this step change can be attributed to increased outages due to newly imposed environmental constraints, it’s important to continue to track these data. The results presented previously assumed a 12-year average for forced and maintenance outage rates. Additional cases using the more recent 5-year outage rates have been initiated. Based on results to date, key results and trends do not change. This has implications for future planning. HNEI is working closely with HECO to address these changes in outages.

These results have important implications for power system planning and policy for O‘ahu. Even with full buildout of Stage 1 solar + storage resources, the AES retirement could increase reliability risks. Recently announced delays of Stage 1 projects indicate buildout of Stage 1 by the time AES is retired may be under 100MW. By the time Stage 2 is deployed, the AES retirement reliability risk is fully mitigated.

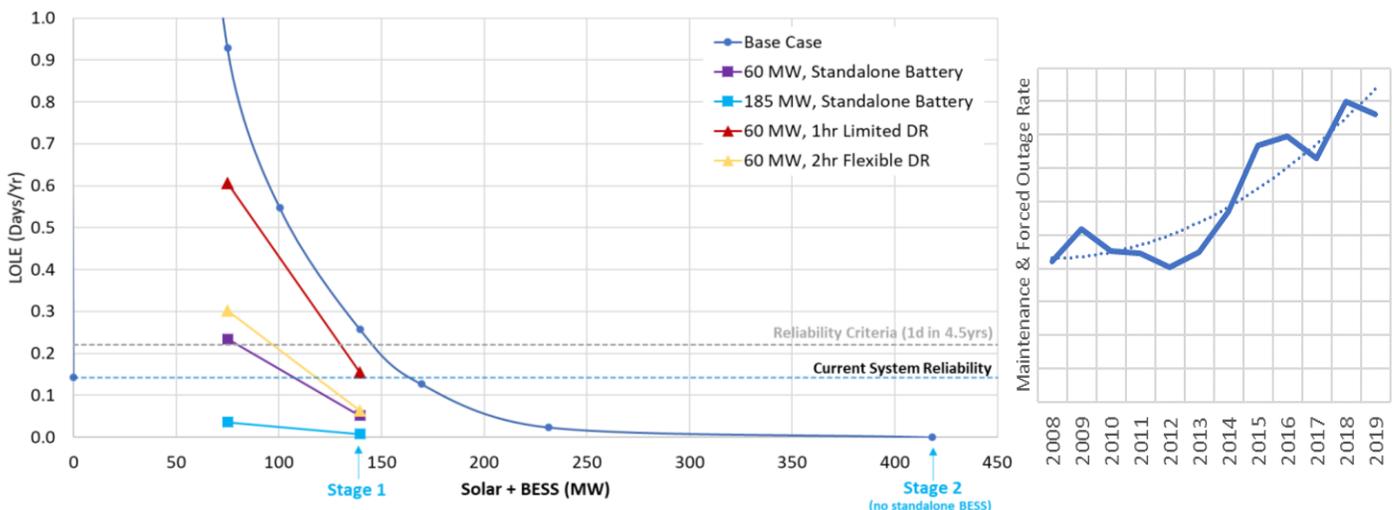
While standalone storage would effectively mitigate the reliability concerns other solutions may be in the best interest of ratepayers. These may include:

- Accelerate Stage 1 and Stage 2 projects through incentive payments, streamlined permitting, and/or increased engineering budgets;
- Temporarily continue operation of AES, beyond the current PPA term and legislative mandate,
- Adjust maintenance schedules in 2023 by deferring planned outages and other elective maintenance;
- Increase energy efficiency, demand response, and behind the meter storage deployment;
- Contract temporary diesel gensets;
- Temporarily adjust the reliability criteria, update involuntary load shedding schemes, and make outages as least disruptive as possible.

*Funding Source:* Office of Naval Research; Energy Systems Development Special Fund

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*Last Updated:* November 2020





# Hawai'i Natural Energy Institute Research Highlights

## Appendix A: Hawai'i Energy Policy and Analysis

### A4: O'ahu Grid Stability with High Solar + Storage Integration

**OBJECTIVE AND SIGNIFICANCE:** The objective of this activity was to evaluate the dynamic stability of the O'ahu grid after a sudden loss of the largest generating unit. Specifically, the analysis was intended to identify any potential concerns regarding stability of the O'ahu grid following the upcoming retirement of the AES coal plant and addition of the Stage 1 solar + storage projects.

As the Hawai'i grids are transformed to include large amounts of solar and solar + storage, it is important to understand the dynamic behavior of these systems. An unstable response of the grid to such an event could result in significant levels of load-shedding with interruption of electric service to customers and even a potential black-out of the entire O'ahu grid.

**KEY RESULTS:** The new screening tool, described in Appendix A2, developed for the purpose of assessing dynamic grid stability for each hour of an entire year (8,760 hours) of grid operations was used to perform a stability screening analysis for two scenarios; one with AES retired and a second for the retirement of AES with the addition of the Stage 1 solar + storage projects. The results show that dynamic frequency stability of the grid is improved with retirement of AES. While the addition of the Stage 1 projects slightly degrades the response relative to AES without the addition of the Stage 1 projects, the response to the largest contingency event further improves if the solar + storage Stage 1 projects are configured to provide fast frequency response (FFR). These results are discussed in more detail below.

**BACKGROUND:** Events like a sudden loss of a power plant challenge the stability of the grid because the unexpected loss of generation throws the grid "off-balance." This is because generation and load must always be balanced on any electric grid. When a power plant suddenly goes offline, for instance, due to a weather event or equipment failure, the result is a generation deficit as the total load does not change immediately after the event. The generation deficit must be corrected in a matter of seconds in order to avoid a blackout of the entire grid. This means that resources on the grid must recognize the generation deficit and begin responding in fractions of a second. The two means of correcting the imbalance are increasing power generation from other sources and/or reducing load by disconnecting customers.

Another related grid event is a sudden loss-of-load, where there is suddenly an excess of generation on the grid that causes an imbalance that must quickly be corrected to keep the grid stable and operating. In the loss-of-load event, generation must be quickly reduced to match load. Because it is generally easier for grid resources to quickly reduce generation than to increase generation, this analysis did not consider loss-of-load events, but focused on the more challenging loss-of-generation events.

Historically, the inertia from the generators in conventional power plants provide an inherently stabilizing dynamic response to such grid events by immediately increasing power generation, while the ability of inverter-based resources to provide a stabilizing increase in power generation, depends on the inverter's controls. FFR is one example of a type of inverter control function that supports the dynamic response of the grid by quickly injecting or absorbing additional power in response to changes in grid frequency in order to quickly restore balance to the grid. Furthermore, FFR does not require any external communication (like a command from the grid operator) to work. This means that grid resources, both utility-scale and distributed, can have the autonomy to respond quickly to emergency events to keep the grid operating.

**PROJECT STATUS/RESULTS:** To determine the impact of the changing generation fleet on grid reliability (stability), the response of the grid to a challenging, yet credible, grid event is studied. This begins with the 8,760 dataset output from a production cost simulation that contains the details of grid operations (total load, generator dispatch, and production of wind, solar, storage) for each hour of a year for a given scenario analyzed. For each hour of the dataset, a dynamic simulation is performed for the loss of the single largest (highest-dispatched) generator on the O'ahu grid during that hour, using the new screening tool. The loss of the single highest-dispatched generator is selected because it is the worst-case generation contingency considered in transmission planning studies.

The output from each dynamic simulation is a measure of grid stress and customer impact resulting from the loss of generation event. The "stress on the grid" is quantified by the grid frequency nadir

(excursion from the nominal 60Hz), where lower frequency nadirs (greater excursions) are indicative of higher levels of grid stress, where the grid is closer to a system-wide blackout. The customer impact is quantified by the amount of load shedding due to the under-frequency load-shedding scheme that was triggered by the event. More grid stress (lower frequency nadirs) result in greater customer impact (more load shedding).

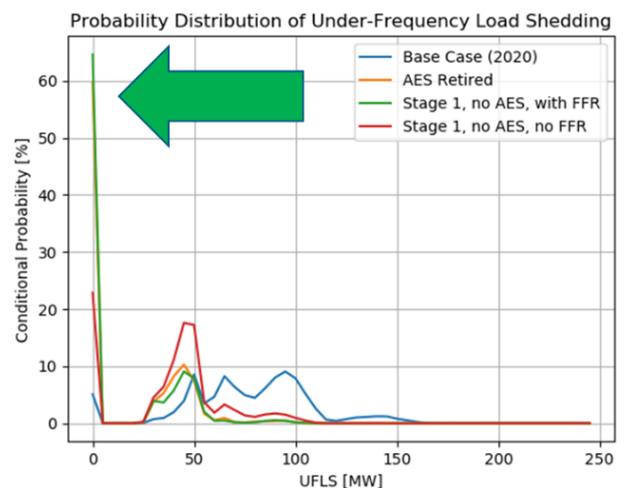
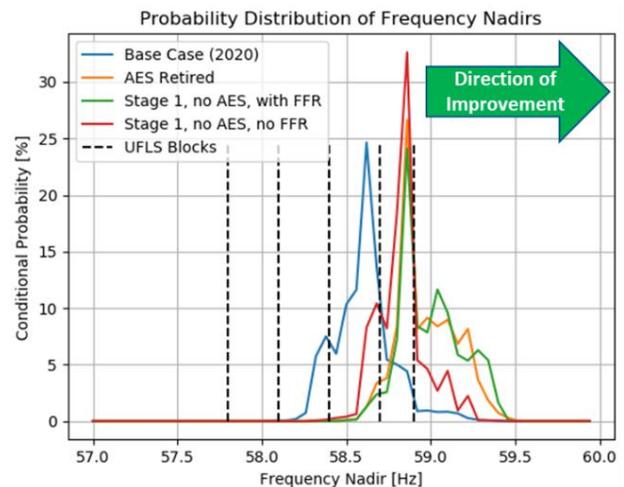
This analysis was performed for the following scenarios:

- Today’s (2020) O’ahu grid;
- The retirement of AES (2022);
- The retirement of AES with the addition of Stage 1 solar + storage projects (without FFR); and
- The retirement of AES with the addition of Stage 1 solar + storage projects (with FFR).

The scenarios with the Stage 1 solar + storage projects were configured in two ways. The first assumed that the plant’s inverters could not provide FFR by rapidly injecting power to the grid after a contingency event. The second assumed the plants could provide FFR and help restore frequency by injecting power rapidly (milliseconds) after an event. It should be noted that the technology is capable of providing this response, but the actual reserve provision is dependent on contractual terms and inverter control settings.

Because the analytical tools simulate a potential contingency event across every hour of the year, it generates significant data – with over 70,000 values across 4 scenarios – results are summarized as probability distributions. Each curve shows the likelihood of reaching a certain level of stress on the grid or load shedding level, given a trip of the largest generating unit at the time.

As shown in the next figure (top), the retirement of AES and the addition of Stage 1 projects moves the probability distribution to the right – an indicator of improvement, since the greatest excursions move closer to the nominal 60Hz value that utilities always try to maintain and farther away from 57.0Hz where the grid would blackout. The companion figure on the bottom shows that the amount of customer disconnection (UFLS) moves to the left – closer to zero, where no customers would be impacted by a worst-case loss-of-generation event.



In comparing the blue and orange traces of the plots, this analysis shows a significant improvement in the dynamic stability of the O’ahu grid for loss-of-generation events with the retirement of AES. This result is counter-intuitive because it is showing better grid stability for a shift away from conventional resources, which we know have a stabilizing impact on the grid because of their inertia contributions. Because AES is the largest single generator on O’ahu – with a potential loss of 200 MW of net load – it is often the single largest contingency. Therefore, by retiring AES, the largest generation contingency is dramatically reduced, resulting in a more stable grid. When AES retires, the largest contingency is reduced to 140 MW loss of Kahe 5 or Kahe 6. This change will help improve dynamic stability because the emergency events will no longer be as severe, regardless of any other potential benefits from the Stage 1 solar + storage projects.

The addition of Stage 1 projects without FFR following the retirement of AES shows a slightly negative impact on the dynamic stability of the grid for loss-of-generation events (when compared against the case without the AES retirement and no Stage 1 projects), as shown by a comparison of the orange and red curves in the plots. While this scenario is still much better than the Base Case, it is slightly worse than the AES retired case because the additional Stage 1 renewables is displacing other conventional resources and not reducing the size of the worst-case contingency.

However, the addition of Stage 1 projects with FFR shows an improvement in grid stability over the scenario with Stage 1 projects without FFR, as shown by comparing the red and green traces of the plots. In this case, the provision of FFR from Stage 1 projects improves the dynamic stability of the grid such that there is no negative impact to stability resulting from the Stage 1 projects, as shown by the similarity of the orange and green curves of the plots.

The shift away from conventional technologies and towards inverter technology (solar + storage plants) constitutes a major change in the way the electric power grid responds to challenging grid events like the sudden loss of a power plant on the grid. As the system continues to evolve towards increasing percentages of inverter-based technologies (solar, storage, wind), the behavior (software-defined controls) of the inverters will become increasingly important to the dynamic stability of the grid. This goes beyond simply enabling useful features like FFR, but also ensuring correct tuning of those features.

This new analysis tool will be applied to look at more future scenarios that consider the addition of more solar + storage (Stage 2) projects as well as the retirement of additional conventional power plants like Waiiau 3 and 4 to inform stakeholders of risk to grid stability and assess the benefits of grid-services like FFR. In addition, a closer examination of the inverter behavior is warranted to determine an appropriate balance fast-response and stable response, which is an inherent trade-off in inverter controls.

*Funding Source:* Office of Naval Research; Energy Systems Development Special Fund

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*Last Updated:* November 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix A: Hawai'i Energy Policy and Analysis

### A5: Curtailment and Grid Services with High Penetration Solar + Storage

**OBJECTIVE AND SIGNIFICANCE:** The Hawaiian Electric Company (HECO), with approval from the Hawai'i Public Utilities Commission (PUC), is negotiating power purchase agreements (PPA) for substantial amounts of utility-scale solar + storage assets in Hawai'i. The design and operation of these resources is expected to impact the ability to integrate these new resources into the grid, their ability to provide grid services, and on grid reliability. The objective of this study was to assess the impact of PPA structures and plant configurations on curtailment when large amounts of solar + storage are added to the grid and to identify how these solar + storage resources could be leveraged to increase value and flexibility.

**KEY RESULTS:** HECO is completing PPA negotiations that will add large amounts of utility scale PV, with the typical project having four hours of storage, based on plant nameplate capacity. The addition of storage to these future PV deployments significantly reduces but does not eliminate curtailment. Mitigations, such as the retirement of AES and cycling of select steam units, that provide additional "space" on the grid for variable renewables was found to significantly reduce the risk of curtailment. It was also found that curtailment likely occurred due to lack of load in the evening and nighttime hours, not a result of insufficient storage.

In addition, the current DC-connected systems and PPA structures that limit charging from the grid to achieve full tax credits may miss significant reliability benefits. Infrequent charging from the grid during rare events increases benefits to the system. Additional analysis is being conducted to quantify these potential benefits.

**BACKGROUND:** At the end of 2018, the Hawai'i PUC approved eight utility-scale solar + storage projects collectively referred to as "Stage 1." These projects, totaling 275 MWac of solar and 1,100 MWh of battery storage, are expected to be operational by the end of 2022. Of this total, 140 MW of solar with 558 MWh of storage is proposed for construction on O'ahu. In a second solicitation, referred to as "Stage 2," HECO selected an additional seven solar + storage projects, totaling approximately 500 MW solar and 2,150 MWh of storage statewide that includes up to 287 MWac solar and 1,275 MWh of storage on

O'ahu. In addition to these projects, HECO is currently soliciting proposals for up to 235 MW of solar under their Community Based Renewable Energy (CBRE) efforts that are likely to include additional battery energy storage.

These changes are taking place against the backdrop of other significant changes to the grid, notably the retirement of the AES coal plant, the largest fossil generator on the O'ahu grid. As a result, it is important to understand how the proposed solar + storage projects can be optimally utilized to ensure efficient grid operations in the future.

The primary use case of the proposed solar + storage projects is to mitigate potential oversupply of solar resources in the middle of the day and to shift energy into evening peak and overnight periods. This decreases the need for oil units to cycle on and off, reduces peak load, offsets more expensive oil-fired generation used during overnight periods, and minimizes curtailment. Details of the battery charging will depend on utility requirements and in some cases, restrictions in the PPA agreements, but in general, the optimal dispatch that minimizes total generation costs shows that battery charges to near full capacity during the day, then discharges during evening peak and overnight hours. The battery then discharges more during the morning load ramp and is near minimum state-of-charge by the beginning of the next daytime period.

Optimal economic dispatch shows that a significant fraction of the solar energy goes directly onto the grid. This is because any solar energy that cycles through the battery will incur additional round-trip efficiency losses of approximately 10 to 15%. As a result, if there is available room on the grid for more PV, the PV will flow directly to the grid, displacing oil-fired generation at the time the solar is produced. Additional constraints such as minimum state-of-charge and use of the battery for grid services will also impact the battery charging.

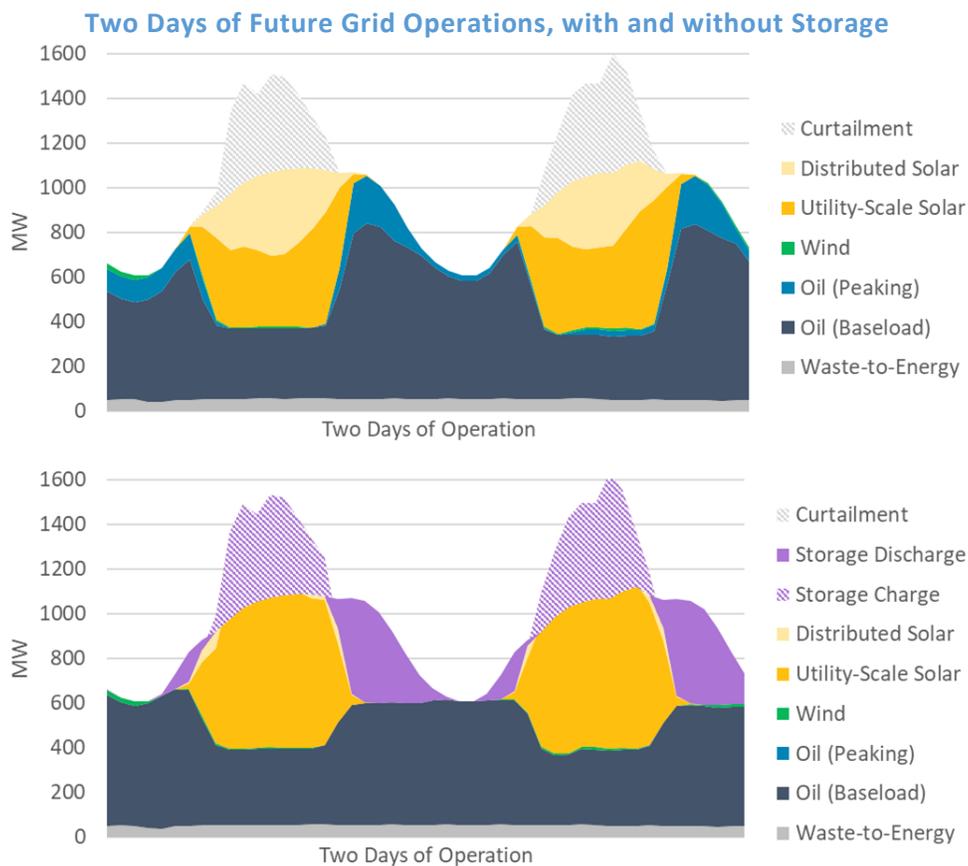
The figure on the following page illustrates the potential operations of the O'ahu grid over a two-day period for two scenarios of solar deployment. The top chart shows representative grid operations with the addition of 800 MWac without storage while the bottom chart shows the same two days with 3200

MWh of storage included. In this example, all the energy that is curtailed without storage can be accommodated on the grid when storage is added. At higher penetrations, this is not the situation.

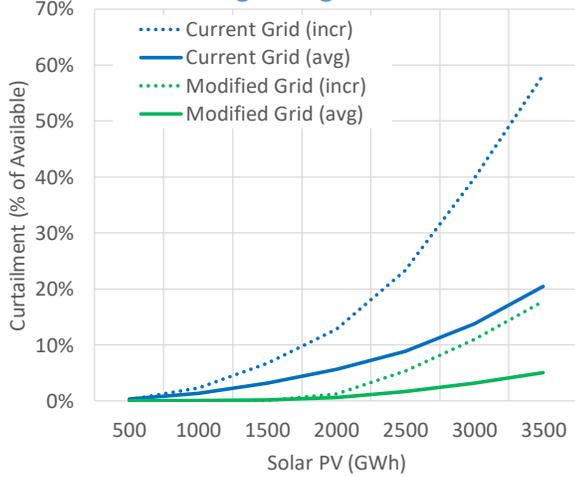
**PROJECT STATUS/RESULTS:** To understand the utilization of solar + storage at very high penetrations, a series of grid simulations were conducted with increasing blocks of solar capacity. Each block comprised 200 MWac of PV (500 GWh annually), with 800MWh of storage. Each block represents approximately 6.5% of O‘ahu’s annual energy needs. Blocks were added up to an additional 3500 GWh, which, when combined with existing renewables represented a 70% renewable share (~80% RPS). The optimizations were conducted for two grid configurations, representing different thermal generation resource mixes. The first represents the “Current O‘ahu Grid,” and includes all fossil generating units currently in operation and must-run operations for the baseload steam oil units. The second represents a “Modified O‘ahu Grid,” in which the AES coal plant is assumed to be retired and the

steam units can cycle on and off, providing increased grid flexibility and more “room” for accepting variable renewable energy onto the grid.

While storage will delay PV curtailments, it will not eliminate them. As shown in the figure on the following page, solar integration with AES still operational results in significant curtailment even when storage is included. With 1500 GWh of additional solar, overall curtailment reaches 3.2%. This curtailment increases to 20% of the total solar generation when 3500 GWh are added. More importantly, incremental curtailment of the last solar added rises quickly from 7% for the third 500 GWh block to just under 60% for the last block. With the retirement of the AES coal plant and ability for the baseload steam oil units to cycle offline or turn down to lower loading levels, curtailment is greatly reduced but not eliminated. Additional constraints may change these results when reliability and grid services are considered. Appendix A3 discusses in detail potential reliability issues when AES is retired.

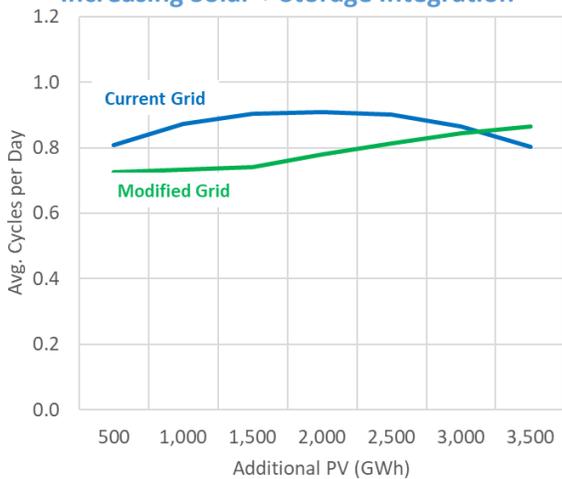


### Solar Curtailment with Increasing Solar + Storage Integration



As shown below, batteries on average cycle less than one time per day under optimal operations, indicating that curtailment is not, in general, driven by the lack of available storage capacity but rather by “space” on the grid to discharge during evening and overnight periods. At a certain point, there is not enough load in the evening to adequately discharge before the solar generation starts again the next day. This may be alleviated by cycling select steam units or with further retirements, but this requires a more detailed evaluation including a careful analysis of grid service needs.

### Average Daily Storage Cycles with Increasing Solar + Storage Integration



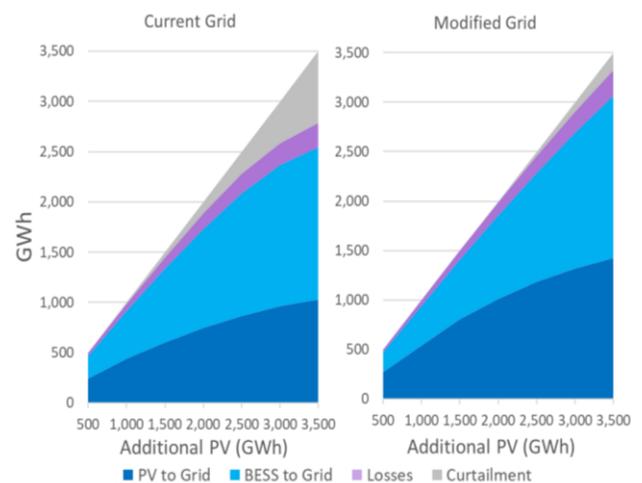
As noted previously, this analysis does not support adding additional storage as a means to mitigate curtailment. In fact, as shown in the previous figure, the daily average cycles per day is less than one for

both grid configurations and for all additional blocks of solar + storage. In this analysis, a battery cycle is measured as the amount of round-trip *energy* that is charged and discharged relative to the capacity rating of the storage.

Under Current Grid assumptions, cycling duty of the storage increases as PV increases through 2,000 GWh of installed PV, but then decreases. This is attributed to a lack of evening load to fully discharge before the next day begins. While still averaging less than one cycle per day with the AES retirement, battery usage increases with increasing PV penetration. In this case, the additional “space” on the grid resulting from the AES retirement and steam-cycling allows more PV to go directly to the grid and more efficiently uses the available storage. Changes to load or load profiles as may occur with the addition of electric vehicles (EV) would likely modify this behavior.

The figure below, shows this from another perspective. This figure shows the fraction of the solar energy (aggregated for the year) that goes directly to the grid, goes to the grid via the storage, as losses in the system, and the amount that is curtailed. As noted above, the additional “space” on the grid resulting from the retirement of AES allows a larger fraction of solar-generated energy to go directly to the grid, reducing the fraction required to be stored for evening with a substantial reduction in curtailment.

### Solar Energy by End Use



In Hawai‘i, most battery installations will not be standalone, but instead will be coupled with an adjacent solar PV system with shared plant and

transmission infrastructure similar to the trend seen throughout the country. There are several other reasons for this trend:

- Investment Tax Credit: As long as storage is charged 75% from renewable energy it qualifies for the ITC, which can offset up to 30% of the initial capital cost;
- Shared infrastructure: Hybrid projects share the same transmission infrastructure across both solar and storage systems;
- Simplified procurement: Hybrid projects allow utilities to bundle the procurement into a single PPA and purchase the renewable energy and storage services on a simple \$/MWh basis, streamlining the regulatory approval process; and

While the hybrid configurations bring many advantages, including those listed above, they can also introduce both technical and contractual restrictions that result in additional operating constraints. Across North America, the majority of solar + storage projects are developed in a DC-coupled configuration because it captures additional energy due to “clipping losses” attributed to high DC:AC ratios and shared transmission interconnection infrastructure. However, with Hawai‘i’s small, low inertia grids, there may be additional benefits to AC coupling (see figure below). Specifically, AC-coupled solar + storage projects afford more flexibility for system operators as both the battery storage and solar portions of the plant can be used in parallel, effectively doubling the capacity of the resource during critical time periods. This could, for example, negate the need for additional standalone storage.

Fast frequency response has the potential to be especially valuable on the island’s grids. Preliminary model results indicate that AC-coupling can provide up to two times more reserve capability during mid-day hours when system inertia is lowest and increase the total reserve availability by up to 30% over the year. HNEI is conducting additional analysis to assess benefits that may accrue from alternative solar + storage configurations as well as possible benefits that may accrue if direct charge from the grid is also implemented.

Based these results, it is clear that hybrid solar + storage additions can provide significant value to Hawai‘i’s grids, both with the ability to shift solar energy to evening and overnight periods and to provide grid services.

*Funding Source:* Office of Naval Research; Energy Systems Development Special Fund

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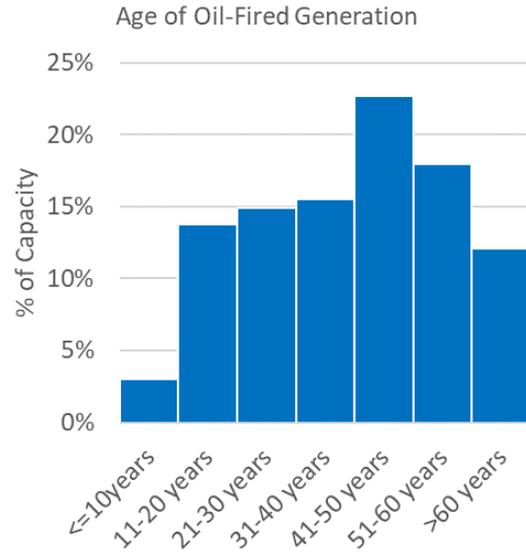
*Last Updated:* November 2020



**OBJECTIVE AND SIGNIFICANCE:** The objective of this analysis was to evaluate the ability of battery energy storage to reliably replace the aging fossil-fired generation fleet in Hawai'i. Specifically, this analysis quantified the capacity value and resource adequacy benefits that energy limited resources provide to the grid to answer the question, "can solar and battery energy storage replace the capacity value of thermal generation?" As the Hawai'i grids integrate additional solar + storage resources, the capacity value metric will be a primary factor in the ability to retire the thermal generating fleet.

**KEY RESULTS:** The results of this analysis indicate that storage systems can provide capacity for reliability, supporting efforts to retire fossil generation. This is based on stochastic resource adequacy simulations using GE Multi-Area Reliability Software (GE MARS) to evaluate system reliability under hundreds of combinations of load, weather, and generator outages. However, as seen in Appendix A3 for the retirement of AES, while storage can provide an effective one-to-one replacement at modest levels of penetration, this work found that the efficacy of storage to provide firm capacity saturates with increasing penetration of storage or solar + storage.

**BACKGROUND:** The average age of the oil-fired<sup>1</sup> power plants in Hawai'i is 40 years with at least one being over 80 years old, arguably the oldest operational fossil power plant in the U.S. Many of the plants are now operating well past their original design life. As the grid transitions to increased wind and solar energy, these plants are used less for energy, but are still being relied on to provide grid services and capacity, especially during periods of low wind and solar production. These plants are also being operated differently, cycling more often and ramping more regularly. The combination of aging infrastructure and increased flexibility demands are leading to increasing generator outages and required maintenance.



At some point, these generators will need to be retired and replaced with newer technology. While wind and solar can replace their energy contributions, a better understanding of their ability to provide capacity benefits is needed for long term planning.

Energy storage, either standalone or paired with solar, is increasingly being used in Hawai'i and across the industry to provide firm capacity and other grid services. Many of these systems are currently planned for deployment in Hawai'i. However, because storage is an energy limited resource and hybrid solar + storage projects are dependent on variable solar energy resources, these resources do not necessarily provide the same nameplate capacity benefits as fossil generation.

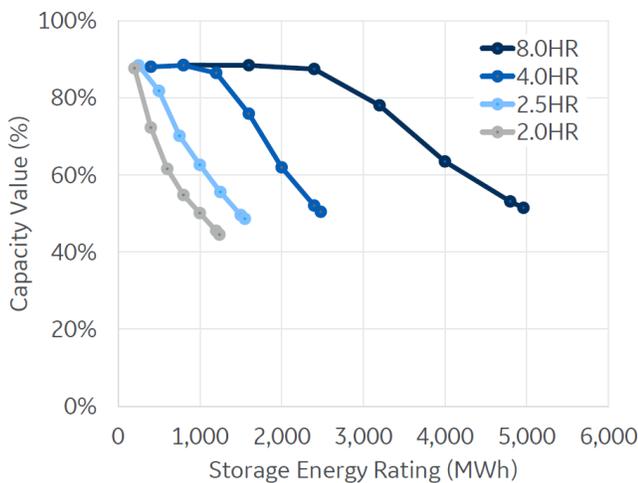
**PROJECT STATUS/RESULTS:** To evaluate the energy storage capacity value, referred to as the effective load carrying capability (ELCC), a series of Monte-Carlo resource adequacy simulations were conducted using the GE MARS. This analysis evaluates generator outages across hundreds of random draws to determine the expected amount of availability capacity and quantifies the number of unserved energy events. Storage resources with different hourly capacities were then added to the system. Load was then added to the system until the original reliability level was achieved. The amount of load added, relative to the amount of storage, determines

<sup>1</sup> Includes low-sulfur fuel oil, diesel, and dual-fueled (diesel and biodiesel) generating units.

the capacity value of the resource.

While early storage additions can effectively replace thermal capacity, as illustrated in Appendix A3, the results of this analysis illustrate that the capacity value of storage saturates as penetration increases.

- With increasing storage and load shifting, the net-load curve starts to flatten, and each subsequent reduction in peak load requires an increasing duration of response, as illustrated in the figure below.
- The state of charge of the storage can vary depending on daily variability of the solar resource.
- At high penetrations, system risk shifts to periods of low solar output, which could last multiple day because of anomalous, but well-understood and historic, weather patterns.



This limits the role storage can have on the system as a firm capacity resource as well as its ability to fully replace the need for conventional thermal generation. However, full capacity credit until 30% of peak load can still provide valuable near-term opportunities for storage to replace aging fossil capacity. To further retire and replace aging capacity, it will require either longer duration storage resources, a larger portfolio of storage and demand response, or other forms of renewable generation.

This work has produced the following publication: 2019, D. Stenlik, et al., “[Energy Storage as a Peaker Replacement: Can Solar and Battery Energy Storage Replace the Capacity Value of Thermal Generation?](#)”, IEEE Electrification Magazine, Vol. 6, Issue 3, pp. 20-26.

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*Last Updated:* November 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix A: Hawai'i Energy Policy and Analysis

### A7: Decision Support Services to the Hawai'i Public Utility Commission

**BACKGROUND:** The Hawai'i Public Utility Commission (PUC) is the regulatory body tasked with reviewing and deciding on key investment decisions, rates, and long-term planning of Hawai'i's investor owned utility, Hawaiian Electric Company (HECO). They are also tasked with reviewing the reliability of the electric power system and its customers. At any point, there may be dozens of dockets under review by the Commission, many of which are based on highly technical and detailed analyses.

The topics under review by the PUC are diverse and multi-faceted. In the past, the PUC has been short-staffed and does not have access to the same modeling tools and skillsets typically deployed by the utility for their long-term planning and docket filings. As a result, having the ability to draw on the expertise of HNEI, and their contractor Telos Energy, provides independent third-party technical expertise to augment the analyses being conducted at the Commission. The flexible nature of this support ensures that work can be deployed in a timely and low cost manner relative to the use of other third-party consultants. This collaboration with HNEI provides a flexible option to quickly analyze both near-term and long-term questions posed by the Commission.

Additionally, under Hawai'i Revised Statutes ("HRS") § 269-92, electric utilities in the state are required to reach increasing levels of renewable generation. Every five years, the PUC is required to publish a report, pursuant to HRS § 269-95, that monitors and measures compliance to the state's Renewable Portfolio Standards (RPS) targets. HNEI is legislatively mandated to perform this analysis of the RPS status every five years for the PUC. HNEI has supported the PUC in a number of these types of analyses since 2017. A number of issues related to the integration of renewable energy technologies have been previously discussed in Appendices A1-A6. Other examples of past support included a review of HECO's distributed energy resources (DER) Grid Service definitions and the economic merits of HECO's standalone battery proposals.

This paper discusses four recent examples of HNEI support to the PUC support:

- Tracking and analysis of the state's RPS targets;

- The impact of COVID-19 on electricity use and potential reliability challenges;
- Lifecycle analysis of greenhouse gases for Hawai'i relevant generating technologies; and
- Analysis of the effective use of the bio-diesel fuel contract at the new Schofield Barracks power plant.

#### PROJECT STATUS/RESULTS:

**RPS Analysis:** In December 2018, HNEI delivered its third RPS assessment to the PUC. The HNEI assessment was the basis for the [PUC report](#) submitted to the state legislature.

This report projected that HECO and Kaua'i Island Utility Cooperative (KIUC) were both on track to meet, and likely exceed, the 2020 30% RPS target. In 2019, KIUC generated 56% of its electricity from renewable energy – already exceeding the 2030 target of 40% – and is on a plan to exceed the 70% 2040 target by the mid-2020s.

Hawaiian Electric Companies generated 28.4% of its total annual sales from renewable sources in 2019 – 25.2% by HECO (O'ahu), 34.7% by Hawai'i Electric Light Company (HELCO) (Big Island), and 40.8% by Maui Electric Company (MECO) (Maui County).

With the completion of the O'ahu "Waiver PV" and West Loch PV projects (157 MW of utility-scale solar PV) and additional distributed rooftop PV, HECO was projected to increase generation by a further 3-4%, exceeding the 2020 target. This is despite the shutdown of the Puna Geothermal Venture plant that remains offline due to the 2018 lava eruption event. Lower than anticipated load due to COVID-19 and related quarantine restrictions should ensure compliance with the 30% target.

Based on the assumed completion of the HECO "Stage 1" and "Stage 2" solar + storage projects, HECO was also reported to be on course to exceed the 2030 RPS target of 40% by 2030. The percentages of renewables for the Hawaiian Electric Companies for years from 2008 and projections through 2025 are shown in Figure 1.

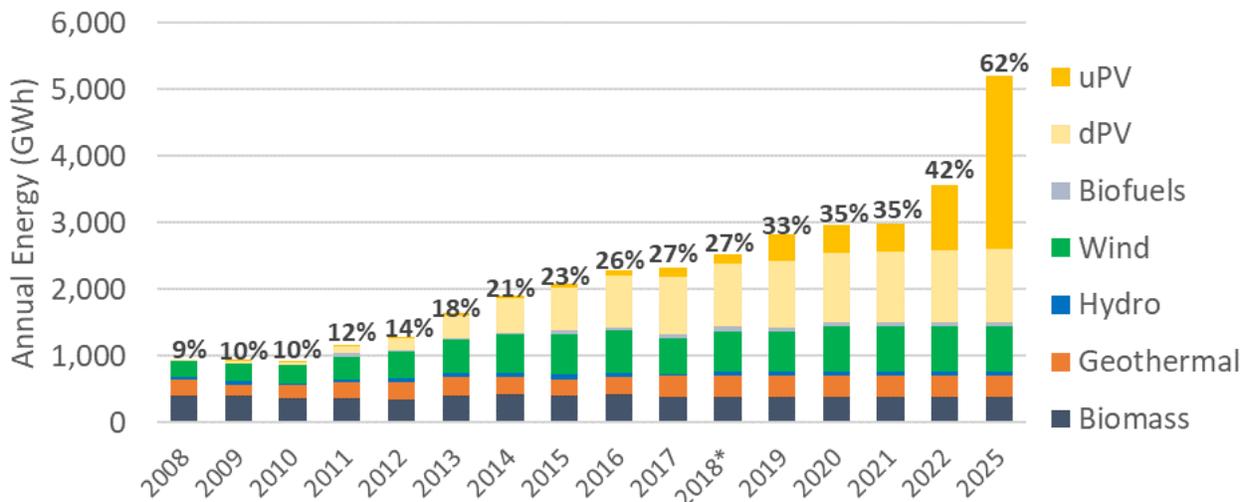


Figure 1. Hawaiian Electric Companies’ percentages of renewable energy by resource, 2008 to 2025.

**COVID-19 Impact on Electricity Use:** In this analysis, HNEI concluded that COVID-19 emergency measures had a significant impact on electricity use in Hawai‘i. HNEI and Telos Energy reviewed hourly generation data to evaluate the effects of COVID-19 and quarantine restrictions on electricity demand. Using O‘ahu as an example, analyses showed that commercial and industrial use dropped, while residential use rose substantially. The results illustrate that, in March 2020, the electricity peak load on O‘ahu dropped from about 1000 MW to about 900 MW, a drop of 10% (Figure 2, below).

Outcomes included findings that: less electricity was used overall; less behind the meter generation was put into the grid; and the “duck’s back” became more pronounced due to the overall reduction of load. The analysis identified potential risk of distributed

generation oversupply if rooftop solar generation was high and load under quarantine measures continued to drop.

The decrease in electricity demand during the middle of the day has the potential to exacerbate impacts on the grid related the “duck’s back.” That is, low loads during the middle of the day could drop to levels below minimum power operational requirements of HECO’s thermal units, which, in turn, would require significant changes in overall grid operations (Figure 3, on the following page).

While the Spring of 2020 saw numerous record-setting renewable penetration levels (as a percentage of load), grid reliability was not jeopardized. This is largely because there was not a confluence such as low load coinciding with peak renewable generation

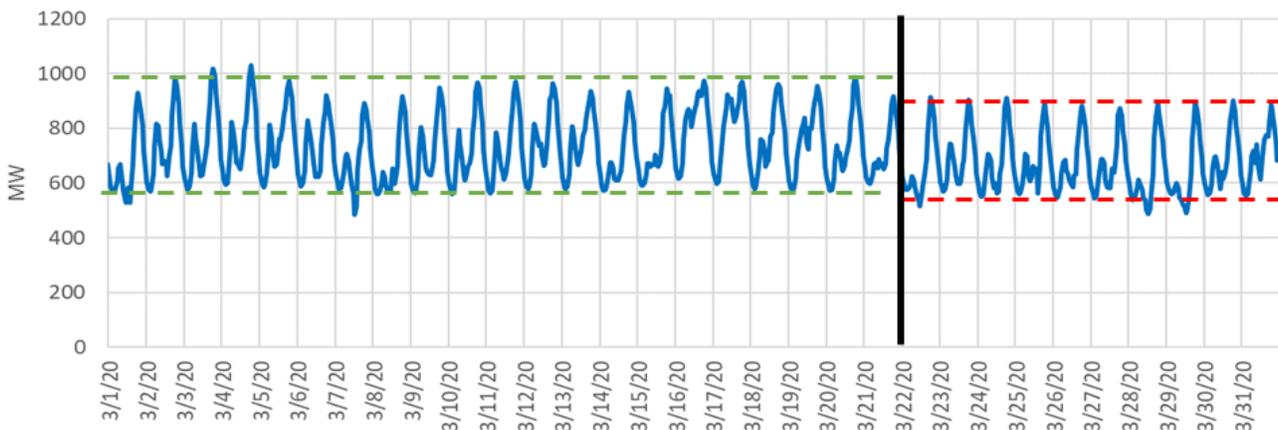


Figure 2. Change in electricity demand following Stay-at-Home order.

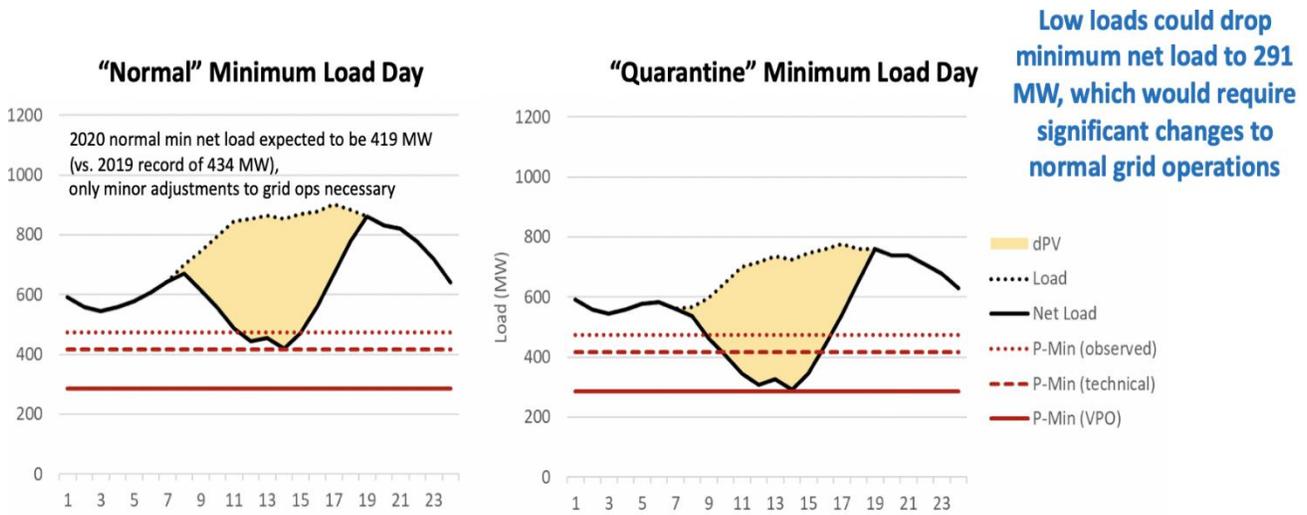


Figure 3. Implications of Quarantine minimum daily load on grid services.

of events such as low load coinciding with peak renewable generation and HECO was able to manage dispatch of the steam oil fleet. However, this analysis was able to check, in a timely manner, if reliability would be challenged.

**Lifecycle Greenhouse Gas (GHG) Analysis:**

Hawai‘i has been in the forefront of integrating renewable energy technologies into its energy mix. In 2008, the state launched the Hawai‘i Clean Energy Initiative (HCEI). The goal of this initiative was to substantially reduce the use of fossil fuels. Since then, there have been a number of modifications enacted leading to the current RPS goal of 100% fossil free energy use by 2045.

While some renewable energy generation technologies do not emit CO<sub>2</sub> at the point of use, there are embedded emissions that are created during the full life cycle of the technology. Therefore, a number of steps must be evaluated to determine the emissions that arise from the production (mining and manufacturing), operation and maintenance, and disposal/reuse of these technologies. In other words, every facet of the any energy technology and resource life cycle will have some GHG emissions, even if the actual production of electricity does not produce any GHGs.

For some renewable resources, like biomass and biodiesel, large amounts of CO<sub>2</sub> may be emitted at time of generation, but depending upon the biomass

source, operations, and life-cycle assumptions, considerable offset of these emissions is possible through new plantings or sequestration.

Recently, the need to perform life-cycle analyses (LCAs) for GHG emissions in Hawai‘i has become more important. The PUC, as part of its decision making, is required to consider GHGs. A number of lawsuits have emerged that require these types of analyses. In late 2019, the PUC requested that HNEI evaluate net life cycle GHG emissions for a number of energy technologies and resources in order to provide the PUC with a Hawai‘i-specific quantitative assessment of emissions from these systems. These analyses will then be used to support the Commission’s decision making. HNEI has completed a comprehensive literature review of existing LCA studies and selected those applicable for Hawai‘i for further evaluation.

HNEI is completing the requested assessment and will soon convene a meeting of stakeholders from Hawai‘i and experts from the U.S. Department of Energy’s (DOE) national laboratory system. Based on available literature and additional analysis conducted by HNEI, a wider than expected range of estimates for lifecycle emissions was found. Even for well-defined technologies, such as PV, substantial ranges were found, partly due to variations in the technology but largely due to variations in the assumptions surrounding the manufacture of the components. For other technologies, such as biomass and biofuels, existing studies can provide general guidance, but

variation in the type of feedstock, the conversion technology, and the final disposition of waste – for example, the re-growth of new biomass resources – requires site-specific studies.

HNEI expects to convene the expert panel in early 2021 with a final report to the PUC in the first quarter of 2021.

**Evaluation of Biodiesel Generator at Schofield Barracks:** In 2018, the Schofield Generating Station started operations. The plant is highly flexible, but has a fuel contract that requires a minimum biodiesel offtake each year and requirements on dual fuel operations. The PUC requested that HNEI review the fuel offtake requirements and evaluate potential operating practices that could be implemented to reduce system costs.

While the price of biodiesel is significantly higher than diesel, a requirement of the contract for this project is a minimum fuel offtake requirement. It was recommended that the cost should be treated as a fixed cost and not be considered when determining Schofield dispatch decisions. Additionally, Schofield is one of the most flexible and most efficient thermal units on the system. It is therefore more economic to utilize the entire biodiesel offtake and fuel blending requirements so that the plant can later switch to diesel fuel. This would allow HECO to capture all of the flexibility and efficiency benefits of the plant while meeting contractual requirements.

*Funding Source:* Energy Systems Development  
Special Fund

*Contact:* Richard Rocheleau, [rochelea@hawaii.edu](mailto:rochelea@hawaii.edu)

*Last Updated:* November 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix A: Hawai'i Energy Policy and Analysis

### A8: Support of Integrated Grid Planning

**OBJECTIVE AND SIGNIFICANCE:** The Hawaiian Electric Company (HECO) under guidance from the Hawai'i Public Utilities Commission (PUC) has initiated the Integrated Grid Planning (IGP) process to determine the types of resources and grid services the utility should invest in over the coming years. A Technical Advisory Panel (TAP) has been established to provide a third-party, technical, and unbiased review of HECO's modeling efforts to ensure it implements best practices and novel techniques being used in other regions. HNEI is currently chairing the TAP, which consists of experts from around the country. HNEI's role as chair is in support of the PUC in response to their request for HNEI to provide leadership in this activity.

**KEY RESULTS:** HNEI's involvement in the IGP and its leadership role in the TAP ensures that HECO will be able to move forward in addressing grid issues related to increasing amounts of renewable energy, which combines both distributed, behind-the-meter generation, and utility-scale projects. Thus, in addressing the IGP docket, HECO receives independent and technical oversight from outside experts. This helps ensure that the utility is using industry-accepted methods, inputs, and assumptions.

Following an initial period in which the progress of the IGP did not fully meet expectations, HNEI was requested to assume an expanded role in supporting the IGP initiative. This increased support has included re-constituting the TAP membership, working with HECO staff to revise their approach for TAP meetings, and assistance in the review of presentation materials to ensure that meetings are as effective as possible. In addition, due to issues that have arisen in Working Groups and with the Stakeholder Council (Figure 1), HNEI has also taken

an expanded role in its participation in these activities.

This approach has been confirmed by the PUC request to HECO for the TAP to play a more substantive role in advising HECO as it moves forward with its integrated grid planning activities. This approach was confirmed in a May 2020 letter from HECO to the PUC.

**BACKGROUND:** By Order No. 35569, issued on July 12, 2018, the PUC opened the instant docket to investigate the IGP process. (Docket No. 2018-0165, Instituting a Proceeding Order No. 30725 To Investigate Integrated Grid Planning.) Pursuant to Order No. 35569, the Companies filed their IGP Workplan on December 14, 2018. The Workplan described the major steps of the Companies' proposed IGP process, timelines, and the methods the Companies intend to employ, including various Working Groups. On March 14, 2019, the PUC issued Order No. 36218, which accepted the Workplan and provided the Companies with guidance on its implementation.

Based on direction from PUC Order No. 36725, Providing Guidance on the IGP, HNEI has taken a leadership role in the IGP's TAP, which is currently made up of industry experts from the United States. Through its November IGP Commission Guidance, the PUC noted that, "[f]or the stakeholder process outlined in the Workplan to effectively serve as a replacement for independent evaluation, the Technical Advisory Panel would have to take an active role in analyzing, evaluating, and providing public feedback on Working Group activities and Review Point filings." The PUC continued by stating its expectation that the Companies "use the Technical

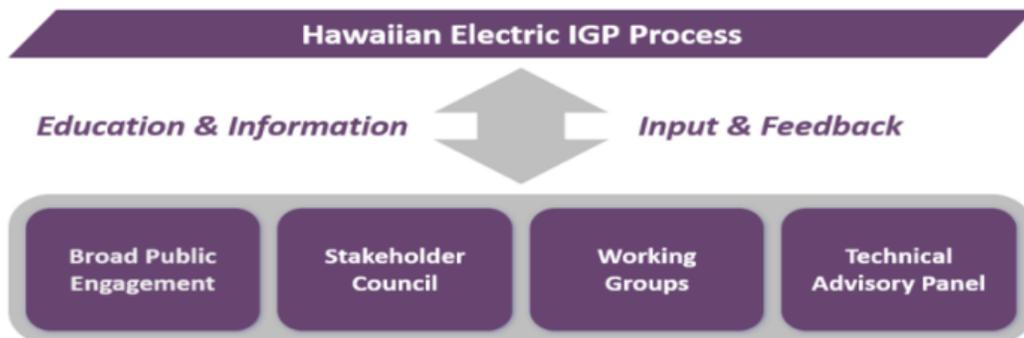


Figure 1. IGP process and participants.

Advisory Panel to provide independent review of each Review Point filing that the Companies will file.” While noting this more substantive approach, the TAP is an independent advisory group and is not a decision-making body, but provides input and advice on the methods and processes that the Companies use to perform such work.

**PROJECT STATUS/RESULTS:** HNEI’s role as the TAP Chair is an ongoing process that is intended to continue throughout the IGP process. This includes regular discussions with the HECO planning team, meetings with the TAP members, and expanded engagement in HECO’s technical working groups. Due to difficulties in ensuring the proper feedback in developing questions for the TAP to address, the PUC developed additional requests (and the utility has accepted and moved on those requests) to have HNEI play a more substantive role in obtaining additional outside experts. Further, this PUC directive allows for HNEI to play a more effective role is assisting HECO in properly formulating questions and agendas for TAP meetings.

On May 27, 2020, HECO responded to the PUC in a lengthy letter that covered a number of topics. One substantive topic was to acknowledge the expanded role of HNEI in leading the TAP and assisting the

company in better preparation for meetings. As seen in Figure 3, there have been delays in meeting the original timelines. This has been due to a variety of factors, one of which is the impact of COVID-19.

As a result of these PUC requests, HNEI increased its interaction with the HECO planning staff to review the status and direction of the IGP process. As part of this process, HNEI also helps create consolidated reporting to better share IGP results with TAP members who may not be aware of Hawai‘i-specific events, trends, or challenges. Finally, HNEI and their contractor Telos Energy, has become more actively engaged in other parts of the IGP stakeholder process, including the Stakeholder Committee and Technical Working Groups. This allows selected TAP members, who are also more involved in these meetings, to have insight and visibility into the complete stakeholder process, without burdening the full TAP membership.

*Funding Source:* Energy Systems Development Special Fund

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*Last Updated:* November 2020



Figure 3. Process flow diagram for IGP.



# Hawai'i Natural Energy Institute Research Highlights

## Appendix A: Hawai'i Energy Policy and Analysis

### A9: Hawai'i Energy Policy Forum

**OBJECTIVE AND SIGNIFICANCE:** Through this project, HNEI supports the activities of the Hawai'i Energy Policy Forum (HEPF) in its mission to enable informed decisions to advance Hawai'i's clean energy future by convening a network of stakeholders for fact finding, analysis, information sharing, and advocacy.

**BACKGROUND:** The HEPF was established in 2002 as a collaborative energy planning and policy group. The organization consists of approximately 40 representatives from the electric utilities, oil and natural gas suppliers, environmental and community groups, renewable energy industry, academia, and federal, state, and local government. It is managed by the University of Hawai'i's College of Social Sciences. In its early years, the Forum was instrumental in several significant areas – including focusing priorities and getting energy issues “on the decision-making table”, promoting funding and needed reform for the State's utility regulatory agencies (i.e., the Public Utilities Commission (PUC) and the Division of Consumer Advocacy), and commissioning studies, reports, and briefings to raise the level of dialog concerning energy issues for legislators and the general public. The Forum sponsors and organizes several well attended annual events, including Hawai'i Clean Energy Day and a Legislative Briefing at the Capitol at the opening of each legislative session, and sponsors programs to develop reliable information and educate and raise awareness in the community. Two HNEI faculty members contribute significantly to HEPF activities, including sitting on the HEPF's Steering Committee, chairing the Transportation and Electricity Working Groups, and hosting and coordinating the weekly ThinkTech “[Hawai'i: State of Clean Energy](#)” show.

**PROJECT STATUS/RESULTS:** During FY 2019-2020, HEPF focused on developing a list of member-driven initiatives, encouraging collaborative dialogue by enhancing the features and usability of the Member Portal, continuing to develop online resources for stakeholders and the general public, and organizing a public briefing. With COVID-19, HEPF is revisiting and adapting its program accordingly. Specific new programs include:

#### ***Strategic Planning***

HEPF held an annual general membership meeting in October 2019 where members revisited HEPF's mission, vision, and values in practice to ensure they are still serving the Forum well, reported on new program initiatives, were provided status updates from various state agencies, discussed next steps for the Forum, and planned for the upcoming public briefing.

#### ***Member-Driven Initiatives***

##### **Peer Exchange Program**

In Fall 2019, HEPF held its first round of peer exchanges (small group policy discussions) on specific shared energy policy and planning issues aimed at encouraging collaborative dialogue amongst members and non-members (including subject matter experts) to inform policy and action. In the inaugural round, HEPF sponsored three peer exchange projects focused on transportation: 1) A Mitigation-Resilience-Equity Nexus Approach to Clean Transportation (led by Kaua'i County); 2) Advancing and Accelerating Hawai'i's Renewable Energy Goals through Clean Transportation (led by Hawai'i County); and 3) Benchmarking Low-Carbon Transportation Policy and Greenhouse Gas Analysis (led by Simonpietri Enterprises). These peer exchanges were instrumental in bringing key stakeholders together (government entities, utilities, academia, for-profit and not-for-profit sectors, and included both HEPF and non-HEPF members) and catalyzing further discussion and action, including introducing templates for a request for proposal and contract for electric vehicle procurement in support of Transportation Services Contracting by State and County governments.

Due to COVID-19, HEPF has continued its peer exchange virtually in 2020. In August, HEPF hosted its first virtual peer in partnership with the Department of Land and Natural Resources (DLNR) to kickstart a project on multi-modal mobility hubs. The State's Climate Change Commission sought and was awarded grant funds from O'ahu Metropolitan Planning Organization and other sources to develop a plan for assessment of state parking facilities statewide that will allow for multi-modal use. The HEPF peer exchange program was aimed at helping determine a general focus for this project.

### ***Online Portal***

HEPF revamped its new Member Portal, that serves as a repository (<https://manoa.hawaii.edu/hepf/>) for membership documents and a space to share information, ask questions, and get feedback. The relaunch helped accomplish one of the Forum's goals to enable greater information sharing and collaboration. It facilitates greater frequency and depth of collaboration one-on-one, as well as amongst a group. The Portal also serves as a springboard for peer exchanges and other projects. The revamp of the portal allows for non-members to have access to certain aspects of the portal to participate in continued discussion from events such as the peer exchanges.

### ***Public Resources and Events***

#### Annual Briefing

In January 2020, HEPF held an Annual Briefing at the State Capitol which focused on aligning energy, transportation, and climate change policy with the needs of Hawai'i residents. The program included comments from Governor Ige and Representative Lowen, a keynote presentation from Scott Glenn (the new CEO of the Hawai'i State Energy Office), discussants from out of state, as well as many specialized HEPF panelists. The final panel included a report out of the Fall 2019 peer exchanges.

#### Online Resources

Between 2019-2020, HEPF developed new resources and updated existing resources for members and the public focusing on policy in the legislature and the PUC. These resources include:

- 2020 State legislature bill tracking spreadsheet, which documents the progression of bills and outlines the final scope of bills passed;
- Updated State Act Database to 1999-2020 (from 2002-2018), which includes topic categorization, and links to the Hawai'i Revised Statutes, act text, and measure history;
- Summary of PUC energy docket proceedings and key updates;
- Compilation of existing federal policies related to energy, which includes a description of the policy (as of June 2020), policy type, relevant sector, managing agency and federal citations to amendments; and
- COVID-19 resources website page providing synthesized COVID-19 related energy

information, which included summaries of COVID-19 docket proceedings that aim to mitigate the effects of the crisis including: cost deferrals, suspending termination/disconnection, and the fuel supply contract between Hawaiian Electric Company and Par Hawai'i. This information was also disseminated via a handout titled 'What's changed since COVID-19? A snapshot of the electricity sector', which includes figures using publicly available data to observe what has happened in the electricity sector since COVID-19.

#### Video Series

HEPF is partnered with ThinkTech Hawai'i to produce five energy-related video streaming series (ranging from weekly to monthly) to inform and engage the public on energy issues, challenges, and actions to advance Hawai'i's clean energy future, available at <https://thinktechhawaii.com/>. Videos are livestreamed and available as recordings.

#### Student Development

Through HEPF, two to three graduate students per semester and one undergrad web designer have been funded.

*Funding Source:* Energy Systems Development Special Fund

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*Last Updated:* November 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix A: Hawai'i Energy Policy and Analysis A10: GHG Reduction from Electrified Transportation

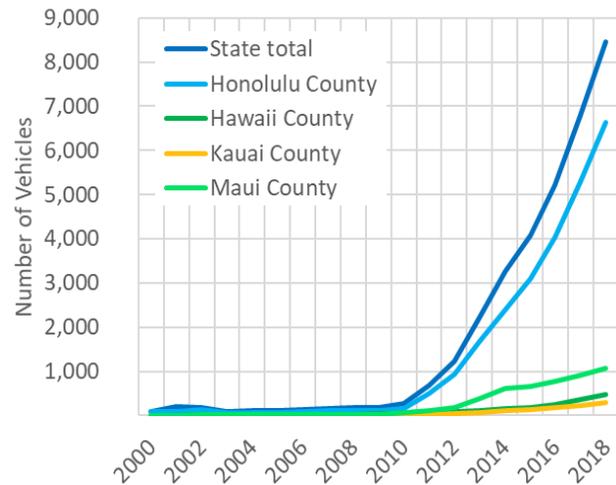
**OBJECTIVE AND SIGNIFICANCE:** Decarbonizing the energy sector in Hawai'i is a key part of the state's energy and environmental objectives. While significant progress has been achieved in the power sector, meaningful reduction in the state's overall emissions, can only be achieved with significant greenhouse gas (GHG) emissions reduction from the transportation sector, which currently accounts for nearly 60% of the state's emissions. Electrification of transportation (EoT), particularly light duty vehicles, has been identified as a key component to meeting these goals.

The objective of this work was to quantify the net GHG benefits of electric vehicles (EV) compared to the current fleet and other vehicle options. The analysis, conducted for the island of O'ahu, included the impacts of increasing penetration of renewable energy generation in the power sector and time-of-day charging of light duty vehicles.

**KEY RESULTS:** The analysis showed that, while the transition to EVs for the light duty vehicle fleet does have the potential to reduce GHG emissions, the reductions will be quite limited until the renewable generation on O'ahu reaches a level requiring substantial amounts of curtailment. Until then, the increased demand for electricity to charge vehicles will require increased oil usage to meet the combined EV and power sector demand. Based on analysis conducted by HNEI, significant curtailment on O'ahu will not occur until renewable generation is far higher than it is today (see Appendix A6). In the short term, greater reductions of GHG can be affected by the replacement of low-mileage internal combustion engine (ICE) vehicles with high-mileage energy-efficient hybrid vehicles.

**BACKGROUND:** As of 2018, there were over 8,400 EVs registered in Hawai'i. While this represents only about one percent of the total passenger vehicle fleet, their share is growing rapidly increasing by 27% annually between 2015 and 2018<sup>2</sup>. If these trends were to continue, there would be over 156,000 EVs by 2030, approximately 20% of today's total vehicle fleet.

Electric Vehicle Registrations



In light of these trends, the Hawai'i Public Utilities Commission opened Docket No. 2018-0135, Instituting a Proceeding Related to the Hawaiian Electric Companies' Electrification of Transportation Strategic Roadmap and associated pilot projects. In 2018, the Hawai'i state legislature also passed [House Bill 2182](#), which set a statewide zero emissions clean economy target, stating that "considering both atmospheric carbon and greenhouse gas emissions as well as offsets from the local sequestration of atmospheric carbon and greenhouse gases through long-term sinks and reservoirs, a statewide target is hereby established to sequester more atmospheric carbon and greenhouse gases than emitted within the State as quickly as practicable, but no later than 2045."

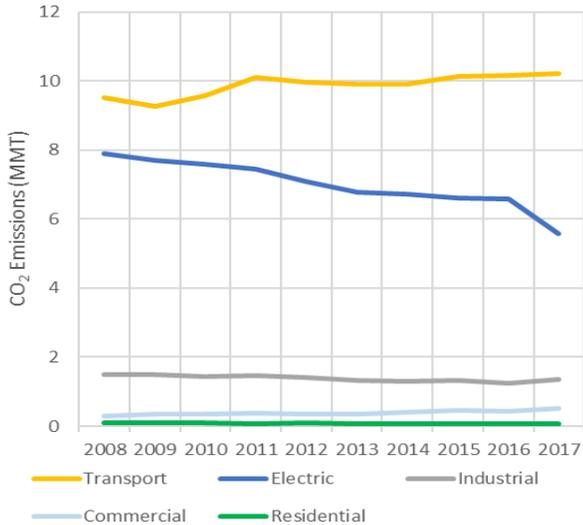
**PROJECT STATUS/RESULTS:** According to the U.S. Energy Information Agency, Hawai'i's statewide CO<sub>2</sub> emissions were 17.7 MMT in 2017, with transportation accounting for 58%, electricity generation accounting for 32%, and the remainder coming from residential, industrial, and commercial uses<sup>3</sup>.

As shown in the figure below, the electric power sector has reduced emissions by approximately 30% since 2008, consistent with the increase in low-emissions renewable generation. However,

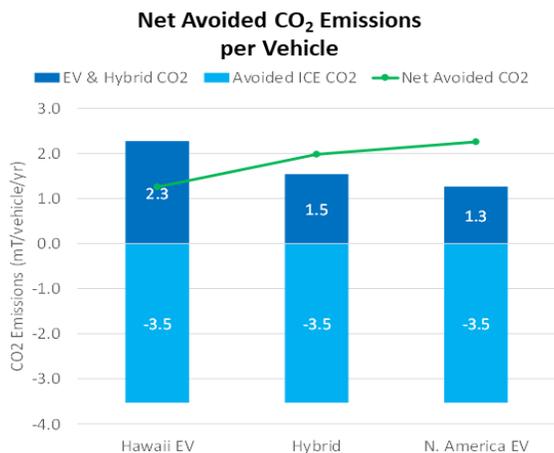
<sup>2</sup> DBEDT State of Hawai'i Data Book, "Table 18.09-- Vehicle Registration, By Taxation Status"

<sup>3</sup> U.S. Energy Information Agency, Energy-Related CO<sub>2</sub> Emission Data Tables, "Table 4, 2017 State energy-related carbon dioxide emissions by sector," <https://www.eia.gov/environment/emissions/state/>.

transportation and other sector emissions have increased slightly during that time. It is important to note that even if all light duty vehicles are electrified, approximately 50% of the transportation emissions result from heavy duty vehicles (7%), marine transportation (12%), and aviation (28%) remain.



While EVs have zero tailpipe emissions, that does not mean they are emissions-free. Instead, the indirect emissions associated with an EV depends on the emissions rate of the electricity produced to charge the vehicle. To understand these results, one has to examine the Hawai'i grid compared to that on the U.S. mainland. Without curtailment of the renewable generation resources, additional EV charging loads require increased oil-fired generation to meet the combined EV-grid demand. This is highly unique to Hawai'i, relative to other North American grids where charging will be incrementally served by lower carbon resources, such as natural gas-fired generation.

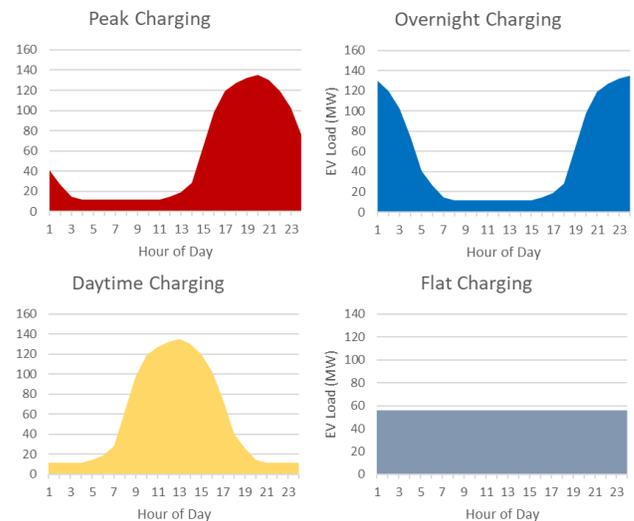


While individual homeowners can reduce their carbon footprint when they have both rooftop PV and EVs, it does little to change the overall island balance. Without the EV, their solar energy generation could have otherwise gone directly to the grid and to offset oil generation.

To understand the role of electrification of transportation in reducing GHG emission, grid models used to evaluate strategies for integration of renewable generation were modified to include different levels of EV adoption, up to 40% of the current light-duty vehicle fleet. This analysis was conducted for O'ahu, which accounts for approximately 70% of the statewide transportation emissions.

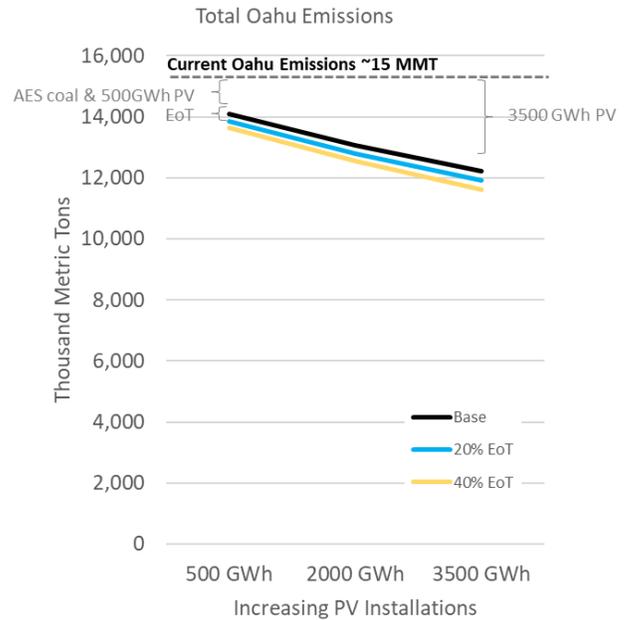
The analysis examined the combined EV-power grid GHG emissions at both near-term and longer-term renewable adoption levels. Specifically, the GHG emissions assumed additional solar + storage installations ranging from 500 GWh to 3500 GWh beyond what is currently deployed on O'ahu, representing up to 50% of the total O'ahu generation mix.

Time-of-day charging is often considered as a means to manage the use of solar for EV charging. To explore this issue, HNEI analyzed grid models for four different charge regimens, shown in the figure below. While there were modest dependencies on when the vehicles were charged, the ability of the utility scale PV + storage to shift energy to when its needed results in minimal impact.



The system-level results of this analysis, summarized in the chart at the bottom of the page, show the combined emissions on O‘ahu from the electric power sector and light duty vehicle fleet at different penetrations of solar + storage energy. It assumes 20% of the current light duty vehicles are replaced by EVs. While electrification of transportation does decrease the vehicle emissions, it is mostly offset by an increase in electricity sector emissions from fossil-fired plants. It is not until O‘ahu reaches very high levels of PV penetration on the grid that the net emissions savings start to substantively increase. For reference, Appendix A6 indicates that with an additional 2000 GWh of solar + storage, curtailment is only 1-2%, reaching approximately 6% with 3500 GWh of additional solar + storage energy generation.

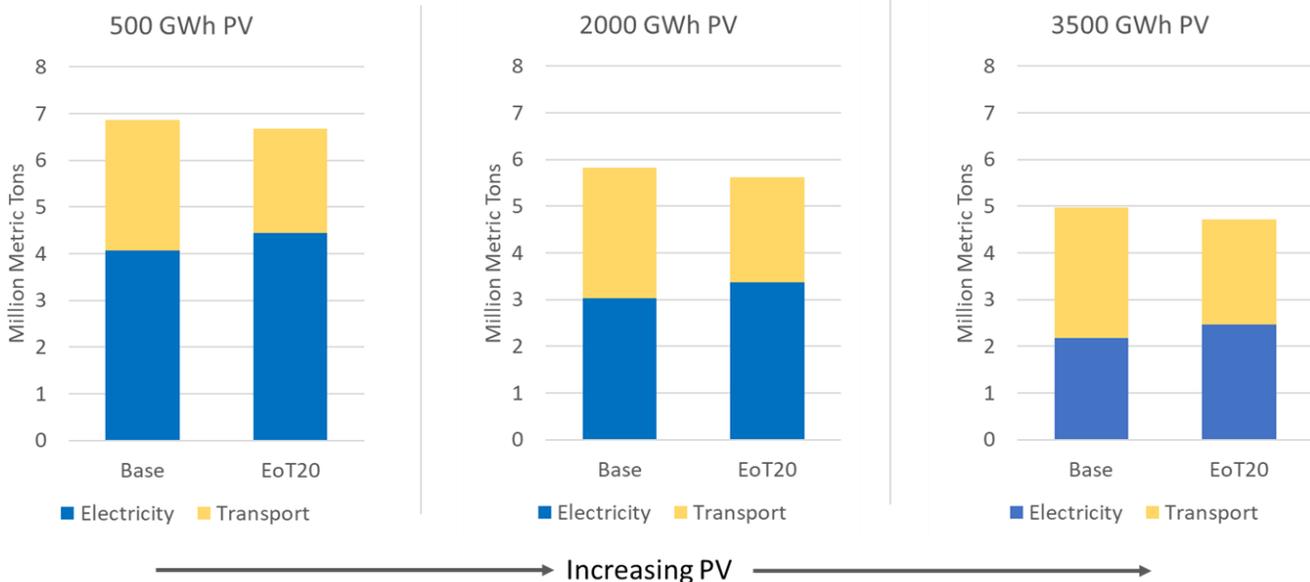
When viewed in the larger context of statewide emissions, EoT has a marginal effect on total emissions. The figure to the right shows that with substantial adoption of renewable energy, a concurrent drop in GHG emissions will occur within the state. However, the electrification of light duty EVs even as high as 40% of the total vehicle fleet, has minimal additional impact on the reduction of CO<sub>2</sub> emissions. For reference, the impact of replacing the AES coal plant with solar + storage has a significant impact.



It is not until the grid is more fully decarbonized that the emissions savings from an EV are higher. However, as solar generation increases, so does the underlying emissions benefits. In a high solar grid, EV charging can be utilized as an effective load management approach and provide valuable grid services. This would allow for further PV adoption and improved emissions benefits.

To date, much of the attention in Hawai‘i’s energy policy and planning has been focused on getting the electric power grid to 100% renewable energy.

**Total Electric Power and Vehicle CO<sub>2</sub> Emissions, 20% EoT Oahu**



Further renewable adoption in the power sector makes sense as there are commercially available technologies available today to make that transition relatively quickly. However, studies suggest that getting the electric power sector to decarbonize the last 10-15% of generation will be significantly more difficult. As a result, if decarbonization of Hawai‘i’s energy system is the goal, it may be more effective to focus on emissions reductions from other sectors, such as transportation, before advancing to a 100% renewable grid.

*Funding Source:* Office of Naval Research; Energy Systems Development Special Fund

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*Last Updated:* November 2020



**OBJECTIVE AND SIGNIFICANCE:** This summary highlights the findings from the evaluation of three grid-tied Battery Energy Storage Systems (BESS) each addressing different issues arising increasing renewable energy penetration levels. The three BESS in this study facilitated the discovery of benefits as well as a number of unexpected adverse consequences arising from this relatively new technology on isolated grids.

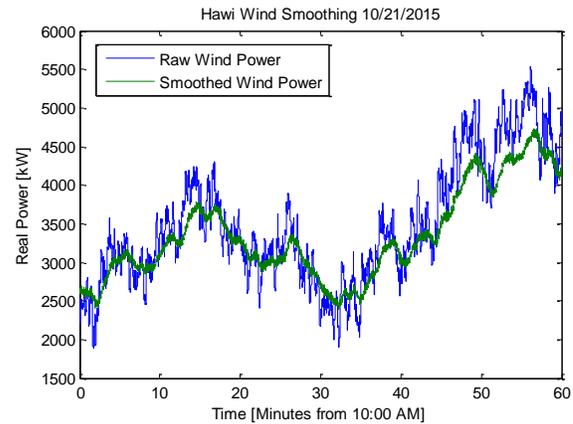
**BACKGROUND:** HNEI entered into agreements with electric grid utility companies on the Big Island of Hawai'i, O'ahu, and Moloka'i to install and test three BESS. Under the agreements, HNEI procured the systems and developed control algorithms. Ownership was transferred to the utilities after commissioning while HNEI retained multi-year data access and testing rights. The first system was installed on the Big Island at a windfarm in the town of Haw'ii, the second on an industrial circuit with high PV penetration on O'ahu, and the third on the island of Moloka'i at its only power station.

The three BESS were designated to test different grid services. The first 1 MW, 250 kW-Hr BESS was installed on the Big Island of Hawai'i and provided either frequency response or wind power smoothing to the 180 MW (peak) grid that hosts 119 MW of renewable capacity. A second 1 MW, 250 kW-Hr BESS installed on O'ahu demonstrated power smoothing and voltage regulation on a highly variable industrial circuit with large loads and significant PV penetration. A 2 MW, 397 kW-Hr BESS was installed on the island of Moloka'i and demonstrated fast frequency response on a low-inertia 5.5 MW (peak) grid hosting about 2.3 MW of distributed PV.

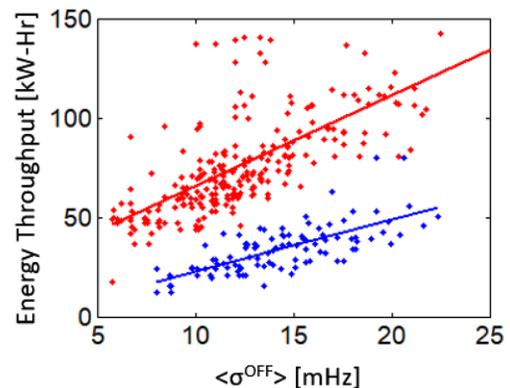
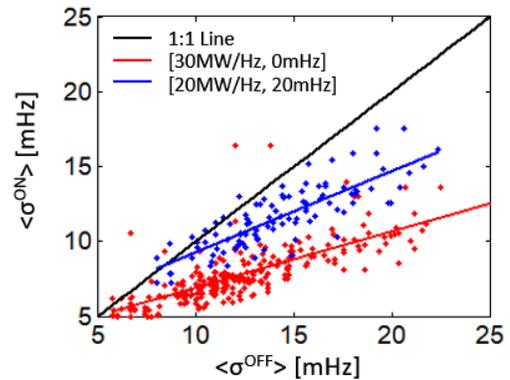
**PROJECT STATUS/RESULTS:**

Hawai'i ("Big Island") BESS:

The Big Island BESS showed significant durability. After 7,500 equivalent full cycles over ~7 years of service the system still operates to specification with only minor repairs. While providing wind smoothing, there were several events where the BESS acted in opposition to the grid's frequency regulation needs so the work focused on use of the BESS for frequency regulation. The chart below shows an example of the BESS absorbing power in the beginning and at the end of an under frequency event.

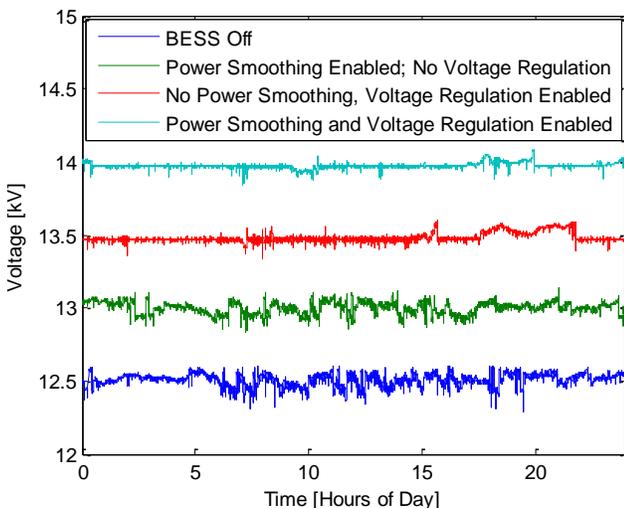


While providing frequency response, the BESS significantly reduced grid frequency variability (top chart below). The use of deadband allowed the BESS to provided strong grid service while minimizing cycling. Cycling was characterized by measuring energy throughput of the BESS. Energy throughput with and without deadband is shown in the bottom chart below. The nomenclature,  $\langle \sigma^{OFF} \rangle$  indicates the mean variability of grid frequency for a 20-minute period just before the BESS was turned on for another 20 minutes, whose variability is denoted as  $\langle \sigma^{ON} \rangle$ .



### Island of O‘ahu BESS

The figure below shows the impact of the O‘ahu BESS on an industrial circuit’s voltage. 500V was artificially added to these traces to avoid overlapping. The variability of the blue and green traces was about 40V when the BESS was offline or only providing power smoothing. The variability dropped to 30V for when the BESS is providing voltage regulation by adjusting its reactive power (red line). When both power smoothing and voltage regulation are used, the variability drops to less than 20V. The voltage regulation service reduced the substation’s load tap changer operations by about 80%. However, the voltage regulation doubled the power consumption of the BESS from 20 kW to 40 kW and excess heating caused isolation faults in the BESS system. This BESS was idle for a number of years prior to installation. Moisture absorbed in the capacitors needed to filter harmonics was the cited cause of an early failure of the system.

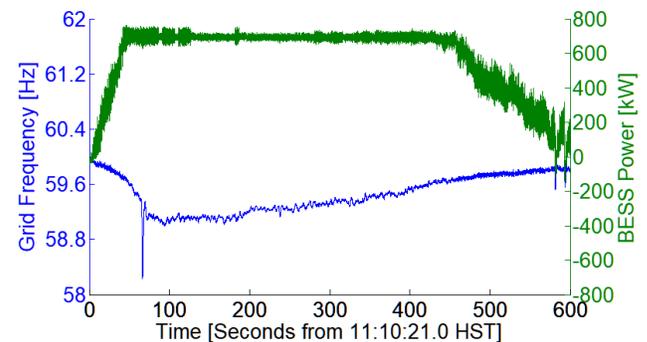


### Island of Moloka‘i BESS

The Moloka‘i system provided several significant insights into the limits of fast frequency response BESS on small, low inertia electric grids. Due to the low system inertia, the grid frequency can swing quickly when relatively small electrical events occur. When those frequency swings breach PV disconnection thresholds, this new contingency compounds the original problem. Early testing also showed that, due to the low inertia, fast frequency response required the BESS to have a response time on the order of 50 milliseconds, something that did not exist in the market. A BESS providing fast

frequency response sources real power to the grid when the grid frequency is low and absorbs real power from the grid when the frequency is high. Latency in this process caused instability on the low inertia grids. This result has important implications for use of BESS on any low inertia system.

The BESS generally provided helpful support, as shown in the figure below where the BESS responded to a frequency drop and then slowly handed the control back to the thermal generators. A review of the data indicates that the BESS likely prevented a number of outages, although there were some anomalies that caused enough concern to the utility so that the 2 MW BESS was limited to 1 MW or less. Specifically, high-resolution voltage data suggests that the cause of these anomalies is related to frequency measurement errors that might also occur in other inverters (e.g., grid-tied PV inverters) on low inertia grids. Several grid meters from disparate manufacturers show a strong drift in measurement sampling times during grid contingencies, such as faults. This topic is currently being documented in a paper.



*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020



**OBJECTIVE AND SIGNIFICANCE:** As summarized in Appendix B1, a fast responding Battery Energy Storage System (BESS) was installed and operated to provide fast frequency response on a low-inertia grid on the island of Moloka'i. Lessons learned from that system that could impact industrial standards for metering and frequency measurement during electrical transients on low inertia grids.

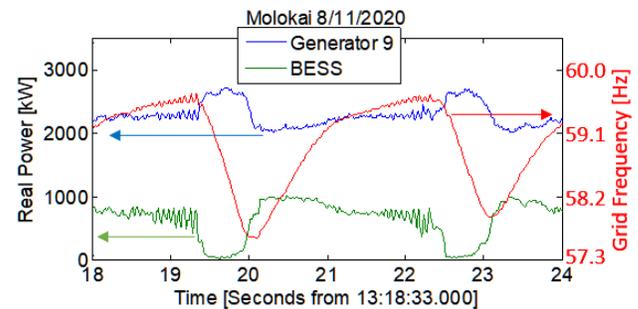
**BACKGROUND:** HNEI and Maui Electric entered into an agreement to install and test a 2 MW, 397 kW-Hr BESS on the island of Moloka'i. The electric grid on Moloka'i is ~5.5 MW (peak) with ~2.3 MW of distributed photovoltaics (PV). The significant PV penetration complicates grid operations; they automatically disconnect when the grid frequency is below a threshold, exacerbating any loss of generation, and they displace traditional generation which has natural mechanical inertia.

Because of the low system inertia, the island's grid frequency can swing quickly when relatively small electrical events occur. When those swings exceed PV disconnection thresholds, the loss of PV generation compounds the original problem. Modeling and experiments also showed that low grid inertia also means that any BESS providing fast frequency response would be required to have a response time on the order of 50 milliseconds to be effective, something that did not exist in the market. A BESS providing fast frequency response provides real power to the grid when the grid frequency is low and absorbs real power from the grid when the frequency is high. Latency in this process can cause instability on low inertia grids.

HNEI funded a BESS manufacturer and an inverter manufacturer to redesign the control path to minimize the system response time as much as possible. The new controls allowed the inverter to measure grid frequency directly rather than wait to receive real power commands from the battery's controller. The redesign reduced BESS response to an event from around 300ms to within 58 milliseconds (typical) which, to the best of our knowledge, is the fastest BESS response reported to date. Live grid testing showed that the redesigned BESS effectively reduced grid instability resulting from conflicts with the island's diesel generators.

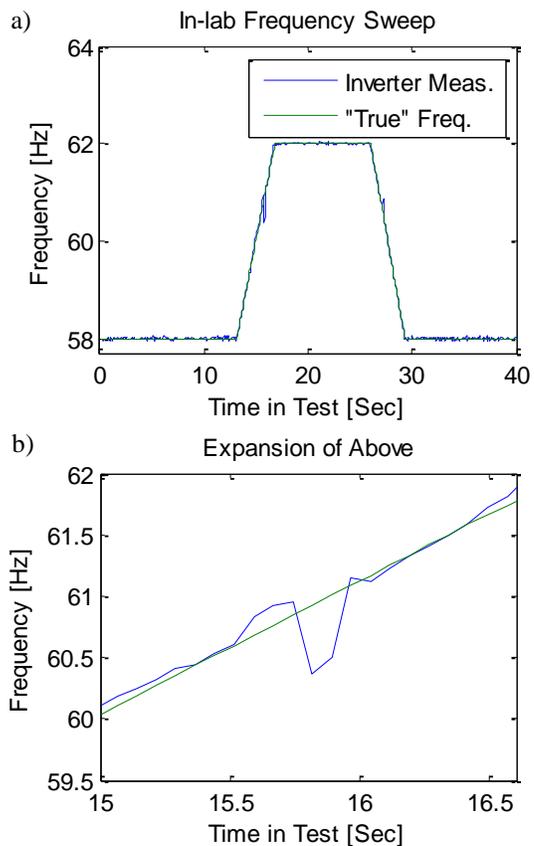
The Moloka'i BESS has been in service since May 2017. As the system's authority (maximum allowable power response) was raised, expected power outages were increasingly avoided. Over the duration of the project, the Moloka'i BESS has responded to many grid events. Based on historical comparisons, the BESS response has eliminated a number of potential grid outages. However, some anomalies were also amplified by the fast response. One anomaly was a fast oscillation in BESS real power and grid frequency. This oscillation was too fast to be explained as conflicts between the BESS and the diesel generators. An oscillation detector was incorporated as a patch into the BESS control software to arrest operations until the oscillations cleared. While the source of the oscillations is not fully understood, a review of laboratory data as well as high resolution measurement on the grid suggests the problem results from how the inverter measures grid frequency. There have been several oscillation events and findings that will be discussed in an upcoming paper. One notable event, that provides insights into the problem from August 11, 2020 is discussed further below.

**PROJECT STATUS/RESULTS:** On August 11, 2020, the BESS responded to a generator outage, supplying real power to mitigate the drop in frequency. However, instead of resolving the problem, fast oscillations in real power were detected and the BESS service was halted. This caused one of the other diesel generators to respond by sourcing more power. Less than a second later, the BESS again began to source real power until another oscillation started, causing the BESS to halt output again. This cycle repeated several times and caused the generator to exceed its power rating of 2.2 MW. This event, shown in Figure 1 below, prompted re-examination of controlled laboratory testing that had been performed on the inverter prior to installation on Moloka'i.



As depicted in the Figure 2 on the right, examination of the laboratory data showed some anomalous behavior. An experiment was run during which the inverter was set to absorb a constant 200 kW while the true frequency (green trace in the figure below) was held at 58 Hz for the first ~12 minutes of the test. The frequency was then ramped up gradually to 62 Hz. While ramping up, the inverter's estimate of frequency (blue trace) diverged from the true frequency. This is shown more clearly in the expanded scale in Figure 2b showing a clear difference between 60.5 Hz and 60.9 Hz. This behavior has now been observed both in the lab and field for various frequency and power combinations. Also, since grid scale inverters are not normally used to directly measure frequency, relying instead on external commands, we are not able to comment at this time about the prevalence of this issue in other types of inverters.

The oscillations shown in Figure 1 occurred when the grid frequency was just below 60 Hz with the inverter supplying ~800 kW, a point that could not be tested in the laboratory. The plausibility of such frequency measurement errors causing oscillations on a small grid in a closed-loop with a BESS is under investigation and will be reported on.



*Funding Source:* Office of Naval Research

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*Last Updated:* November 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix B: Grid Technology Development

### B3: Dynamic Load Bank for Islanded Grid Solutions

**OBJECTIVE AND SIGNIFICANCE:** Under this joint project between HNEI and Maui Electric Company (MECO) a custom controlled Dynamic Load Bank (DLB) was deployed with the objective of demonstrating a reliable and inexpensive means to prevent the baseload diesel generators from operating below their minimum dispatch level during periods of high solar generation. The system enabling the grid connection of additional rooftop PV on Moloka'i island, beyond that originally allowed by the utility. Continuing research in controls is intended to deliver additional grid value from this asset, such as rapid response to system dynamic events. Project lessons will support enabling high penetration of distributed PV systems on microgrids and island power systems.

**BACKGROUND:** Among the challenges faced by utilities to integrate very high levels of rooftop solar PV on isolated island grids is maintaining a minimum reliable operating level of diesel generators during times of high PV production. High PV production can force generators below their required minimum operating point, with the uncontrolled “excess energy” produced by the PV systems degrading grid reliability and operating risk to unacceptable levels.

Moloka'i reached its system-wide rooftop PV hosting capacity in 2015, resulting in a 700 kW queue of new customer applications for rooftop PV. Analysis showed that the potential for excess energy production by proposed rooftop PV systems held in the queue would occur very infrequently. By absorbing a mere 3.9 MWh of excess solar energy with the DLB, additional annual production of a significant 1.1 GWh of clean solar energy is enabled, with a commensurate reduction in fossil energy use.

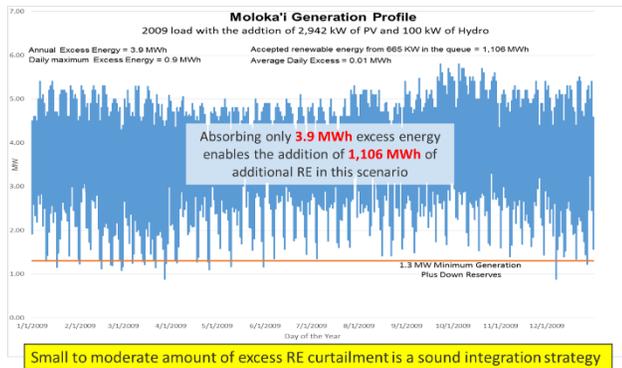


Figure 1. Analysis showing infrequent events of rooftop PV annual excess energy production requiring mitigation by the DLB.

Functioning as a grid “safety valve” to manage infrequent events of excess solar energy production, the DLB solution allowed the grid connection of approximately 100 new customer-sited rooftop PV systems at a cost far below that of energy storage, while ensuring adequate operating reserves and grid stability on the island. The installed DLB and its controller are shown in Figure 2.

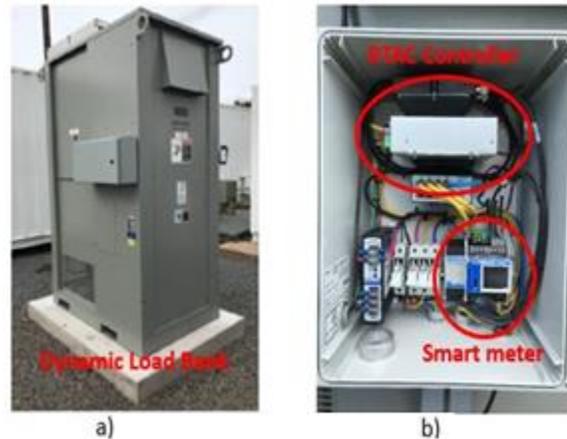


Figure 2. a) The DLB installed at MECO power plant on Moloka'i; b) RTAC controller with the smart meter used for tests.

**PROJECT STATUS/RESULTS:** DLB control algorithms for excess energy absorption were developed, lab tested, and validated via grid simulation. The DLB system was then installed, tested, and placed in service at the MECO power plant on Moloka'i. Successful operation of the DLB allowed 700 kW of new customer-sited distributed PV to be grid tied, following a 3-year period of no new PV system additions. HNEI GridSTART is continuing its valued partnership with MECO to develop additional grid stabilizing control algorithms that can rapidly react to system disruptions, such as sudden loss of generation or load rejection events. Stacking added functionality such as automatic frequency response will increase both utility and customer value return on the very modest investment in DLB technology.

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix B: Grid Technology Development

### B4: Advanced Real-Time Grid Energy Monitor System (ARGEMS)

**OBJECTIVE AND SIGNIFICANCE:** The objective of this project is to develop a low-cost device and system that can provide enhanced situational awareness allowing tighter, localized coordination of distributed energy resources (DERs) such as rooftop solar photovoltaics (PV). This is important for Hawai'i because as power generation and ancillary services become more decentralized and variable, there will be a need for enhanced measurement, data analytics, and distributed controls near the grid edge. Field devices such as advanced meters, line sensors, and secondary reactive power (var) controllers are all part of Hawaiian Electric Companies' Grid Modernization Strategy, and this project has the potential to provide significant advancements in these areas beyond the commercial state of the art.

**BACKGROUND:** Grid edge technology has the potential to relieve voltage constraints with local context-aware volt/var control, identify and help mitigate local thermal violations through energy and load shifting, provide data for more refined and readily updated PV hosting capacity analysis, identify power quality issues such as harmonic distortion from increasing amounts of power electronic devices, and assist in fault location and anomaly detection, such as pending transformer failure and unmetered loads. This system offers a high-tech, flexible research-to-commercialization platform that can be programmed to support these use cases and more. It offers high-fidelity voltage and current measurement, numerous communications options, low-latency event-driven messaging, precise GPS-based timing, backup power supply, and powerful processing capabilities for real-time data analysis, all within a small weather resistant enclosure.

**PROJECT STATUS/RESULTS:** ARGEMS devices have been successfully deployed at the UH Mānoa campus, Arizona State University, Chulalongkorn University (Thailand), and in Okinawa, Japan. The latest version is shown in Figure 1 and examples of analysis and visualization are shown in Figure 2.

The system is currently patent pending (via UH's Office of Technology Transfer) and commercial pathways are being explored. Discussions regarding potential use cases and demonstrations have been initiated with utilities in Hawai'i, Alaska, and Thailand. Assembly is now performed commercially.

Costs are expected to be competitive with traditional distribution service transformer monitors.

The project has enabled and fostered new collaborations and funded research and it has been featured in educational and outreach activities. It has supported research on distributed volt/var control (DURA project led by Arizona State University) and optimal electric vehicle scheduling and charging (vehicle to grid demonstration, with Hitachi). Fourteen (14) undergraduate students and six international interns have been involved. It has been shared with the public through ThinkTech Hawai'i, SOEST's Open House, and UH Sea Grant's Voices of the Sea.



Figure 1. ARGEMS devices ready for research collaboration.

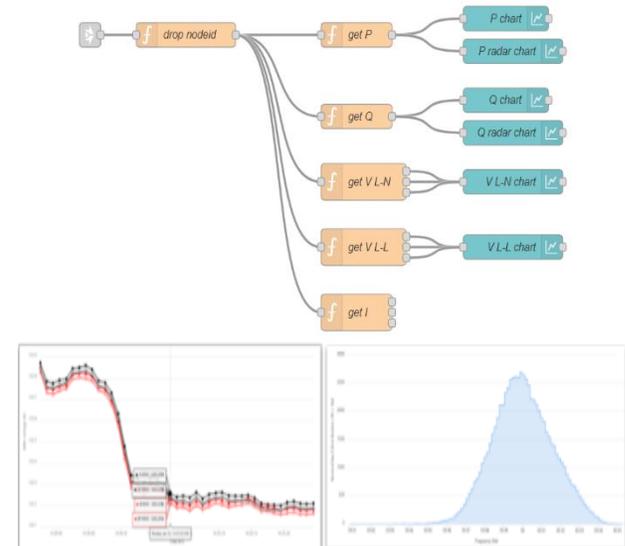


Figure 2. Analysis and visualization of real-time data.

**Funding Source:** Office of Naval Research,; Defense University Research-to-Adoption (DURA) via Arizona State University

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**Last Updated:** November 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix B: Grid Technology Development

### B5: Solar Power Forecasting

**OBJECTIVE AND SIGNIFICANCE:** This project's objective is to develop advanced forecasting methods and technologies to predict solar photovoltaic (PV) power generation from minutes to days ahead. Knowledge of PV system future output will allow grid operators and grid management systems to proactively address the inherent variability of solar power. Day ahead (DA) forecasts support unit planning and scheduling, while hour ahead (HA) forecasts support unit dispatch and operational reserve management, and minute ahead (MA) forecasts predict the timing and magnitude of significant PV ramp events. Solar forecasts also provide visibility and situational awareness for distributed behind the meter solar systems, helping to minimize reliability issues and disruptive events and manage the cost of grid operations with increasing levels of PV interconnected to the electric grid.

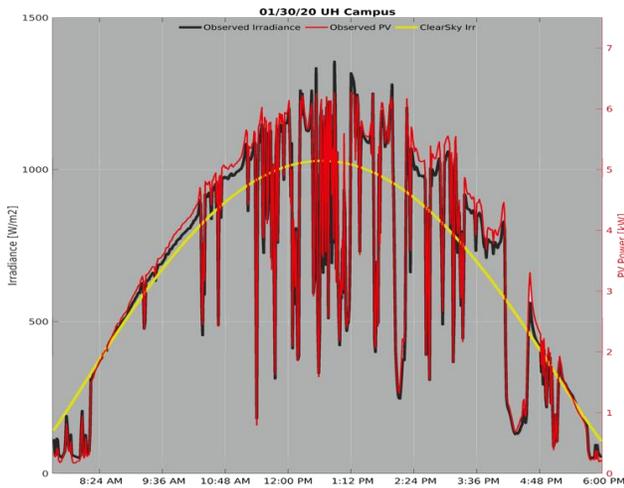


Figure 1. Irradiance observations and PV power measurements from the UH FROG Building on January 30, 2020.

**BACKGROUND:** Power output from PV systems is directly related to the power of the sunlight striking the panel, measured as irradiance. Solar irradiance at the top of the atmosphere varies slowly and predictably, modulated by Sun-Earth geometry and solar variability. Solar irradiance at ground-level varies quickly and erratically, modulated by the absorption and scattering of sunlight by clouds, fog and haze, as well as other particulates, such as dust, ash, and smog. The state of these particles is controlled by complex, nonlinear, and dynamic atmospheric processes, which make PV power output

in most cases highly variable and difficult to predict. A sample day of irradiance observations and measurements of PV output from the UH FROG Building are shown in Figure 1.

HNEI has developed a multi-scale, solar forecasting system capable of monitoring irradiance in near real-time and generating PV power forecasts from minutes to days ahead. This system is fully automated, generating predictions without human intervention.

For DA forecasts (longer than 6 hours ahead), numerical weather prediction (NWP) models are required to account for turbulent atmospheric processes. DA forecasts are generated from a specific configuration and augmentation of the Weather Research and Forecasting (WRF) system designed for solar energy applications.

Geostationary satellite images provide consistent monitoring of regional atmospheric conditions, while ground-based sky camera images monitor local conditions at high resolution (Figure 2). From these images we determine the position, velocity, and optical properties of cloud formations. This information is used to drive cloud dynamics models that estimate future cloud conditions and irradiance at HA and MA time scales.

Using ensemble methods, DA, HA, and MA irradiance predictions are combined to generate probabilistic irradiance forecasts. These probabilistic forecasts are used to drive PV simulation tools to predict PV power.

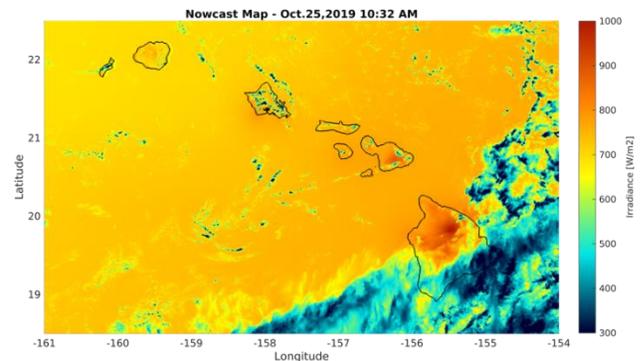


Figure 2. Sample irradiance map from GOES-17 images.

**PROJECT STATUS/RESULTS:** HNEI continues development of an irradiance mapping and prediction instrument for high-resolution irradiance nowcasting and MA forecasting. The instrument is designed for low production cost, wireless operation, and self-monitoring. The latest version of the instrument incorporates more robust electronics and increased computational power to allow for edge computing functionality. A prototype instrument is currently deployed on the UH campus, a sample image can be seen in Figure 3.

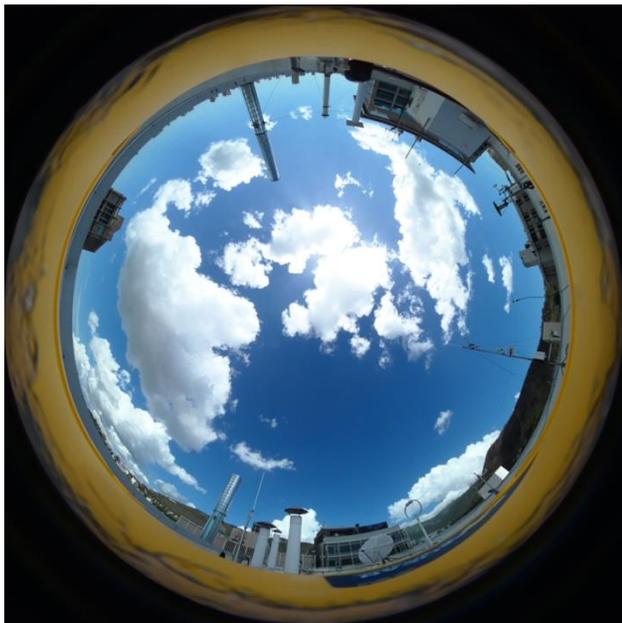


Figure 3. Sky image taken from the UH Mānoa campus on October 25, 2020.

The HNEI solar forecasting system is actively generating operational probabilistic forecasts for the Hawaiian Islands.

Each night, a regional 24-hour ahead forecast is generated from NWP. During daylight hours, a regional 6-hour ahead forecast is generated from NWP and GOES-West images. This forecast is updated every 10 minutes to include information the most recent satellite images.

Tools for forecast data distribution and web-based visualization have been added to the system. The prototype visualization system focuses on the Natural Energy Laboratory of Hawai‘i Authority (NELHA) site (on the island of Hawai‘i), where the National Renewable Energy Laboratory (NREL) maintains

instrumentation that provide realtime irradiance observations. NELHA site forecasts and realtime observations can be viewed at: <http://128.171.156.27:5100/hawaii/>. Figure 4 shows sample output from the visualization system for September 25, 2020 at 12:22 PM HST.

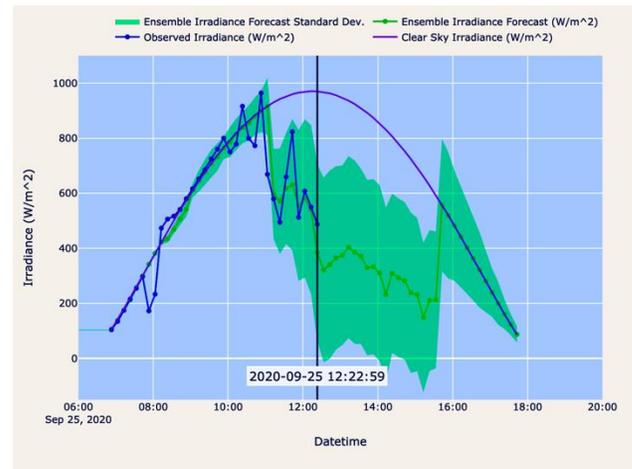


Figure 4. Sample output from the forecasting visualization system for the NELHA site. The probabilistic forecast and ensemble distribution are shown in green, while realtime irradiance observations are shown in blue. The black solid line indicates the current time.

*Funding Source:* Office of Naval Research ; KERI; U.S. Department of Energy, UI-ASSIST

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*Last Updated:* October 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix B: Grid Technology Development

### B6: Coconut Island DC Microgrid

**OBJECTIVE AND SIGNIFICANCE:** HNEI's GridSTART is developing a DC-based microgrid on Coconut Island, home to UH's Hawai'i Institute of Marine Biology (HIMB), in Kāne'ōhe Bay, O'ahu. The project objective is to demonstrate the reliability, resilience, and energy efficiency of a DC microgrid serving two buildings on Coconut Island. The system is intended to support critical building loads during grid supply interruptions, while also providing clean electrified transportation options powered primarily by rooftop solar energy. Results and lessons learned from this project can be utilized for the design and development of future DC-based microgrids at other locations in Hawai'i or abroad.



Figure 1. DC microgrid project site on Coconut Island, Kāne'ōhe Bay, O'ahu, Hawai'i.

**BACKGROUND:** Among HIMB's goals is for the island and its research facilities to serve as a model for sustainable systems. Thus, it serves as an ideal site for a renewable energy technology-based test bed that represents a remote location vulnerable to energy disruption, yet serving critical power needs essential to its mission. Key project goals include:

- Adoption of innovative new energy efficient and reliable clean energy technologies;

- Increase energy sustainability;
- Reduce dependence on the local utility and the existing aged undersea electrical service tie to the island;
- Provide a research platform to study DC microgrid technologies (e.g., microgrid controller, energy storage, and DC powered appliances) in a tropical coastal environment; and
- Support solar powered all-electric land (E-car) and sea based (E-boat) transportation options.

**PROJECT STATUS/RESULTS:** HNEI, in collaboration with the Okinawa Institute of Science and Technology (OIST) and the PUES Corporation, completed the development and deployment of a DC powered E-car, E-boat, and portable emergency power source using a swappable battery storage system primarily supplied by a new 6.2 kW rooftop solar PV system. Additional microgrid elements including DC lighting, DC air conditioning, DC-DC converters developed by the University of Indonesia (a research partner), 8 kW/8 kWh li-ion battery energy storage system, HNEI's GridSTART custom-built DC microgrid controller, power meters and data collection equipment, and balance of system equipment and infrastructure are in an advanced stage of procurement and installation. A schematic of the DC-based microgrid test bed is shown in Figure 2.

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020

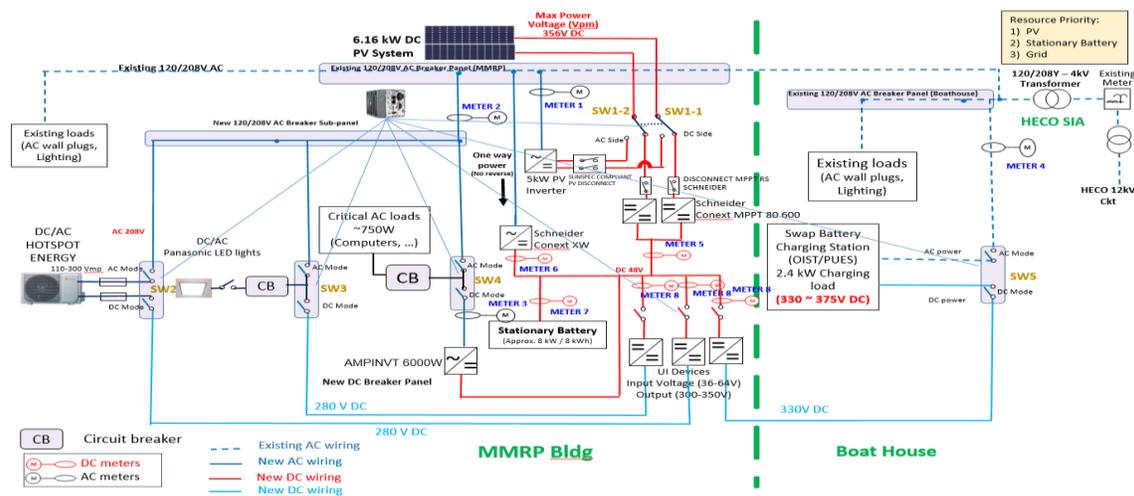


Figure 2. DC microgrid single line diagram.



# Hawai'i Natural Energy Institute Research Highlights

## Appendix B: Grid Technology Development

### B7: Ka Honua Momona: Maximizing Efficiency of Off-Grid Nano-Grid

**OBJECTIVE AND SIGNIFICANCE:** The project objective was to convert an existing off-grid solar PV system comprising 5.1 kW PV panels, battery storage and a backup fossil fueled generator, into a more efficient “smart” nano-grid utilizing site-scale automated load and demand management strategies to minimize wasted generation, while eliminating the need for fossil fuel backup.

**BACKGROUND:** From 2013-2018, Ka Honua Momona (KHM), a not-for-profit community organization in Kaunakakai, Moloka'i operated from an off-grid system consisting of 18 PV panels, dual 7200-watt Outback inverters, 40 kWh of lead acid storage, and a fossil-fuel back-up generator. KHM found that their renewable energy was not used efficiently largely due to varied daily site utilization patterns that range from a very low baseline load (e.g., internet router and refrigerator) to a high load (e.g., large events utilizing air conditioning, lighting, and kitchen loads) that exceeds generation and storage capacity.

To help mitigate inefficiencies in generation and storage and stabilize the nano-grid, HNEI identified three goals:

- To test, compare, and utilize three 9 kWh Sunverge integrated energy storage systems in an off-grid environment;
- To pilot a “smart” generation schema to automatically redirect excess solar energy generation (load dump) to other loads that would be useful to KHM such as water heating and water distillation; and
- To identify practical design issues when using multiple battery banks and multiple inverters.

**PROJECT STATUS/RESULTS:** HNEI implemented a “smart” strategy installing water heaters as a variable load for excess generation. Two water heaters use small, Heliatos™ solar thermal water heaters to provide nominally sufficient hot water for the baths. The solar thermal hot water is then augmented by Sunverge integrated energy storage units after their batteries are fully charged and are in “float” condition. This load diversion is precisely controlled by solid state auto transfer switches that transfer power to the water heaters when the battery voltages are one volt below “float” voltage and will cutout load

diversion when the batteries are two volts above low battery cutout (LBCO).

On the power supply side, PV panels initially charge the primary battery banks. Once the primary batteries reach full capacity, a solid state transfer switch that detects voltage shifts the solar generation to a secondary set of batteries at predetermined battery voltage condition. As these secondary batteries reach full capacity the energy is redirected a third 50 gallon water heater or a small water distillation system, thereby utilizing renewable energy that would have been wasted otherwise.

This off-grid system was designed to adapt to highly variable usage patterns and load conditions. This project is ongoing through December 2020.



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*Last Updated:* October 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix B: Grid Technology Development B8: NELHA HOST Park Microgrid Analysis

**OBJECTIVE AND SIGNIFICANCE:** The objective of this project was to determine the feasibility and benefits of modifying the current energy system at Natural Energy Laboratory of Hawai'i Authority (NELHA)'s Hawai'i Ocean Science and Technology (HOST) Park to enable it to operate as a microgrid (or a number of microgrids) connected to the Hawai'i Electric Light Company (HELCO) electric grid system, or as a stand-alone facility. The study will determine those distribution system configurations providing optimal benefit to NELHA, the HELCO grid, and both together. A secondary objective is to maximize the use of renewable energy resources available within the HOST Park.



Figure 1. NELHA's HOST Park site and existing HELCO primary distribution feeder.

**BACKGROUND:** Microgrids, especially those integrating renewable energy resources, are of interest in Hawai'i for their potential to enhance the reliability of the microgrid site and host grid, to increase energy assurance, improve security, and potentially reduce cost and carbon footprint. Microgrids can also improve resilience against both manmade and natural disruptions. The Governor of Hawai'i signed Act 200, which directed the Hawai'i Public Utilities Commission (PUC) to open a proceeding to establish a microgrid services tariff to encourage and facilitate the development and use of microgrids throughout the State. NELHA's HOST Park facility has been identified by the PUC as a potential microgrid demonstration site for advanced technologies to enable grid resiliency. Along with techno-economic resource optimization, HNEI will identify regulatory and policy issues currently in place that hinder the development of microgrids and

offer modifications to those regulations and policies for future action.

To achieve the overall project objectives, a power system requirements analysis of the HOST Park based on NELHA's energy projections for a 10-year period will be conducted. Both the technical and regulatory/policy opportunities and barriers will then be assessed, with potential on-site distributed generation, energy storage, power management, and control technology alternatives evaluated to identify the most promising ones applicable to a microgrid or microgrids at the NELHA HOST Park. The work will deliver microgrid conceptual design options that meet NELHA's technical and economic power requirements over the 10-year planning horizon.

**PROJECT STATUS/RESULTS:** HNEI's GridSTART, in collaboration with NELHA staff, identified the existing and planned power generation and distribution infrastructure and requirements for the HOST Park. This work included a review of NELHA's HOST Park utility metered accounts, historical energy use and power demand, utility rate structures, distribution infrastructure, critical load priorities, load service reliability, existing emergency and renewable generation resources, and forward projected power needs. An integrated assessment of these energy system elements with the HELCO distribution infrastructure that serves the HOST Park has yielded conceptual microgrid design options. Detailed feasibility, techno-economic analysis, and optimization of these conceptual microgrid options continue.

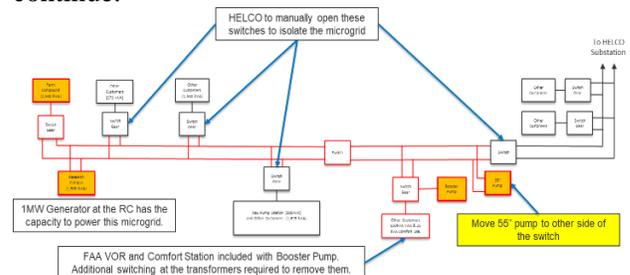


Figure 2. Potential HOST Park microgrid configuration for extended utility grid outage.

**Funding Source:** Hawai'i State Energy Office via NELHA

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**Last Updated:** October 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix B: Grid Technology Development

### B9: Advanced Conservation Voltage Reduction Development & Demonstration

**OBJECTIVE AND SIGNIFICANCE:** The objective of this project was to demonstrate conservation voltage reduction (CVR) as an effective ways to save energy. The main principle of CVR is that energy and peak demand can be lowered by up to 0.9% for each 1% reduction in voltage level.

**BACKGROUND:** The primary value proposition of CVR implementation – reduced energy use by more effective management of customer service voltage with an expected reduction in energy consumption in the range of 0.7% to 0.9% for every 1% reduction in voltage. Working in close collaboration with Marine Corps Facilities personnel in Okinawa, seven distribution service transformers on a branch of the 13.8 kV circuit serving the Plaza Housing complex was identified for CVR field test and evaluation.

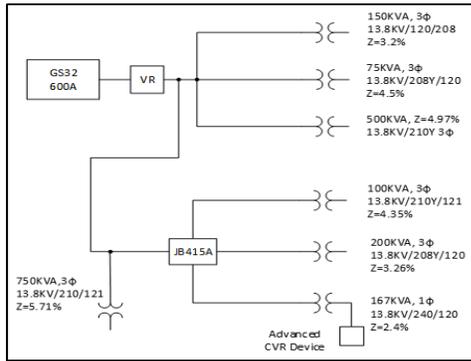


Figure 1. CVR Demonstration Single-Line Diagram.

The CVR controlled feeder section is isolated with a new voltage regulator (VR) to control the voltage at “downstream” service transformers, essentially behaving like a substation transformer load tap changer (LTC) for the section of the feeder under test. The LTC action of the VR shifts the voltage profile of the feeder up or down, but is unable to manage individual low or high voltage points along the feeder path. Voltage reduction by the LTC is thus constrained by the minimum voltage point along the feeder. HNEI has patented and field demonstrated a method of localized voltage management with an advanced CVR device to: (1) smooth the voltage profile; (2) boost the lowest voltage at a distribution service transformer, thereby allowing the LTC to further shift the entire feeder voltage down; and (3) provide maximum CVR benefit for all customers.

**PROJECT STATUS/RESULTS:** Utilizing HNEI hardware-in-the-loop (HIL) laboratory platform, testing and validation of the CVR control algorithm

developed by HNEI’s GridSTART, including communication between the controller and field meters to be located at service transformers was completed.

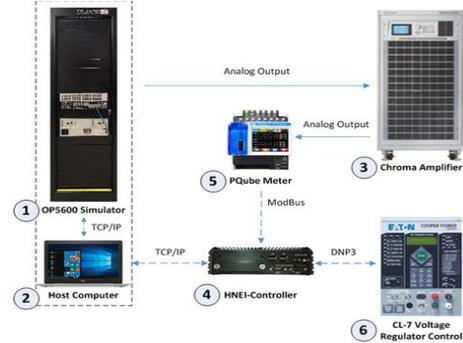


Figure 2. CVR real-time HIL test set-up.

Multiday real-time HIL simulations using field voltage measurements collected from the project site were used to ensure robust and reliable operations of the HNEI-controller and algorithm under a full range of load conditions.

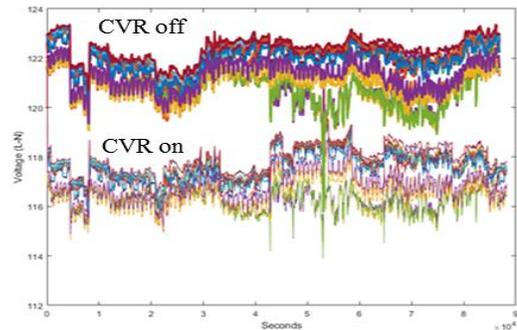


Figure 3. Voltage Profiles with CVR on and off.

Field design and construction of all CVR system components and a 5.8kW rooftop PV system is complete, with civil/structural work performed by Navy Seabees. Project operational commissioning is pending the lifting of COVID-19 travel restrictions.



Figure 4. Project construction by Navy Seabees and new PV system.

*Funding Source:* UH ARL; Office of Naval Research

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*Last Updated:* October 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix B: Grid Technology Development

### B10: Sustainable Grid Platform with Enhanced System Layer and Fully Scalable Integration

**OBJECTIVE AND SIGNIFICANCE:** The objective of this project is to support the long-term goal of designing highly scalable technologies for distribution systems to operate reliably and securely with extremely high penetration of distributed energy resources. The results from this three year project, conducted by HNEI as a subawardee to the University of Central Florida (UCF), will provide a scalable solution that can be adapted to grids of various sizes, and facilitates the integration of additional distributed energy resources.

**BACKGROUND:** The project overview is summarized in Figure 1. The expected outcomes of this project includes:

- A modular, plug-and-play and scalable Sustainable Grid Platform (SGP) for real-time operation and control of the distribution network;
- Advanced distribution operation and control functions to manage extremely high penetration solar PV generation (installed PV capacity > 100% of distribution feeder peak load) in a cost-effective, secure, and reliable manner; and
- Software and Hardware-in-the-loop (HIL) test platform.

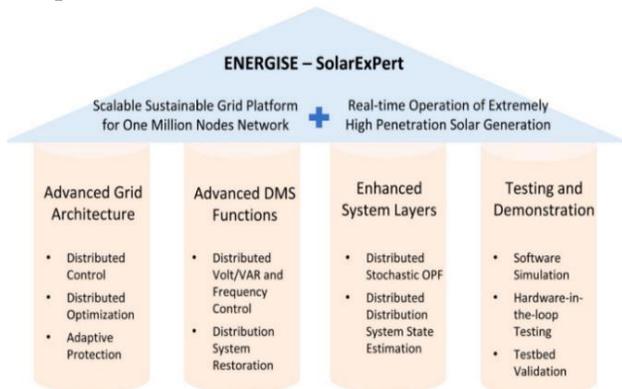


Figure 1. SolarExPert project overview

HNEI's GridSTART developed, tuned, and calibrated the detailed electrical model of a very high PV penetrated distribution feeder on the island of Maui based on an extensive collection of field measured data previously captured in the course of U.S. Department of Energy (DOE) and Office of Naval Research funded research projects. This high-fidelity electrical model is used in the testing and tuning of the open source software of the SGP and advanced distribution management system functions developed by UCF.

**PROJECT STATUS/RESULTS:** In this, the third and final year of the project, a distribution circuit PV hosting capacity estimation approach based on stochastic analysis was developed. The high-fidelity model of Maui island distribution feeder with extremely high penetration distributed PV was utilized to determine the impacts of advanced inverter control functions on PV hosting capacity. Uncertainties in the location and size of the future installed PV systems are considered based on historical PV data. The PV size sampling result is shown in Figure 2.

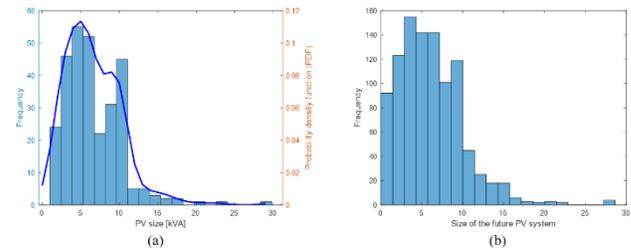


Figure 2. (a) histogram of the 295 installed PV systems and the estimated probability distribution; (b) histogram of the sizes of the future PV systems.

The PV hosting capacity analysis focused on feeder voltage quality, particularly on voltage rise as a function of installed PV capacity relative to local load. The hosting capacity improvement with advanced solar PV inverter Volt/VAR and Volt/Watt optimization control algorithms are illustrated in Figure 3. The boundaries determine the minimum and the maximum hosting capacity.

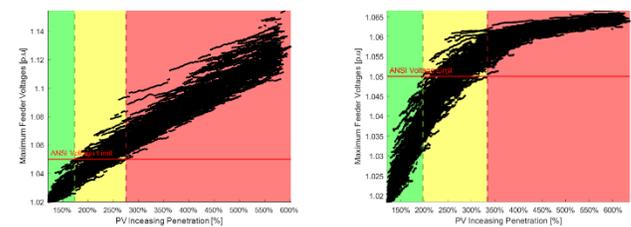


Figure 3. The PV hosting capacity of the Maui test feeder: (a) without the voltage control algorithm; (b) with the advanced Volt/VAR and Volt/Watt control algorithm.

This project was successfully completed in August 2020. Final reports to DOE are being prepared.

*Funding Source:* U.S. Department of Energy

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*Last Updated:* October 2020



**OBJECTIVE AND SIGNIFICANCE:** The objective of the research activity is to synthesize a full set of disaggregated solar photovoltaic (PV) and customer load data from a limited number of field measurements to enable more realistic distribution feeder modeling and state analysis for circuits with high distributed PV penetration. Actual field metered measurements of customer load and PV system production is very limited today, yet effective circuit power flow modeling requires the representation of the individual time-varying energy production and demand profiles at all electrical buses. This work supports the development and testing of distributed control algorithms for distributed energy resources on a feeder with high penetration of distributed PV.

**BACKGROUND:** Under the earlier U.S. Department of Energy funded Maui Advanced Solar Initiative, HNEI deployed approximately sixty (60) distribution-level power monitoring devices to capture high resolution data at key nodal points located at distribution service transformers, PV inverters, and residential homes. In conjunction, a detailed electrical model was developed as shown in Figure 1. The rooftop PV systems and customer loads are marked with green and red circles, respectively. This feeder serves approximately 800 customers, with a total installed rooftop PV capacity of approximately 2 MW and a daytime minimum feeder load of 975 kW, a PV penetration level of more than 200%.

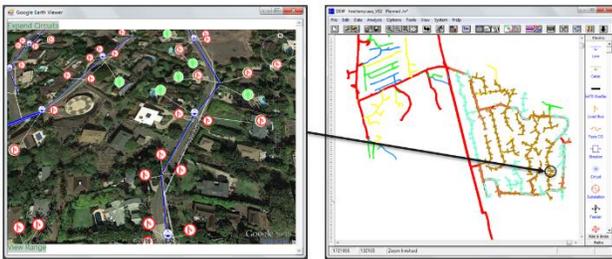


Figure 1. Maui Meadows distribution circuit.

**PROJECT STATUS/RESULTS:** HNEI's GridSTART developed a spatial-temporal algorithm to estimate the PV generation at 280 nodal points based on limited field collected data of nearby PV systems. The PV data set (field and synthesized), total feeder net load, and measured net load at each distribution service transformer are the inputs to the stochastic data estimation method for synthesizing gross load at distribution service transformers where field data was

not available. The data flow is shown in the diagram below.

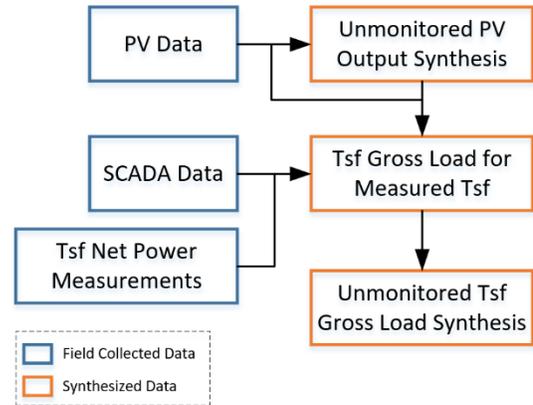


Figure 2. Data flow of PV and load data synthesis.

Validation of the synthesized load and PV data was achieved by injecting it along with the limited field measurements into the electrical model and comparing the voltages from the power flow with the voltages measured in the field. The results are illustrated in Figure 3 below with mean errors for each transformer voltage ranging between 0.16% to 1.47%.

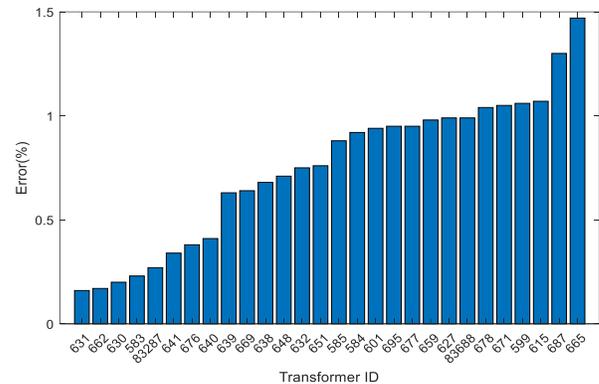


Figure 3. Voltage magnitude error between simulation and field measurement.

The results of this research will be reported in part in a manuscript that was submitted for IEEE's 2021 Conference on Innovative Smart Grid Technologies.

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*Last Updated:* October 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix B: Grid Technology Development

### B12: Marine Corps Base Hawai'i Installation Energy Security Plan

**OBJECTIVE AND SIGNIFICANCE:** HNEI is supporting Marine Corps Base Hawai'i (MCBH) in completing its Installation Energy Security Plan (IESP) to enhance installation energy resilience and improve mission assurance. The IESP will document the current and future energy security requirements of MCBH, its ability to meet those requirements, and plans to address high priority gaps. It will take into account resource constraints, statutory mandates, executive policy, and service-level priorities.



Figure 1. Marine Corps Base Hawai'i at Kane'ohe Bay. (Photo Credit: MCBH)

**BACKGROUND:** On May 30, 2018, the Office of the Assistant Secretary of Defense Energy, Installations, and Environment (OASD-EI&E) issued the memorandum "Installation Energy Plans – Energy Resilience and Cybersecurity Update and Expansion of the Requirement to All DoD Installations," mandating an IESP be prepared for MCBH. The IESP must take into account the capacity, reliability, and condition of the existing energy infrastructure on base and the ability to meet future growth requirements. The IESP is envisioned to discuss, compare and contrast alternatives for energy security and resiliency, and recommend technical strategies and solutions. The solutions are to be based upon technologies that are already proven commercially viable and ready-to-go. Thus, it's intended to deliver an actionable energy plan for MCBH with a focus on resilient, proven, and economically viable energy systems ready for implementation. HNEI's GridSTART and MCBH are cooperating through

regular interaction and exchange to secure necessary information on the electrical infrastructure, plans, operations, critical load priorities, relevant base studies/assessments, and the like to facilitate HNEI's support of the IESP. The IESP includes seven stages and follows the planning framework shown in Figure 2.

**PROJECT STATUS/RESULTS:** An initial draft report of the IESP including stages 1, 2, 3, and 4 has been delivered to MCBH and is currently under review. HNEI continues its work on stage 5 of the IESP. This stage proposes solutions addressing the installation's energy resilience requirement of fourteen days without commercial power. Alternative microgrid designs are being developed and assessed, including a microgrid solution that powers the entire base and smaller microgrids that maintain power to base priority loads. Figure 3 illustrates a conceptual microgrid design that utilizes the existing rooftop PV at MCBH and proposes additional generation and energy storage resources to power the entire base through an extended utility service outage.

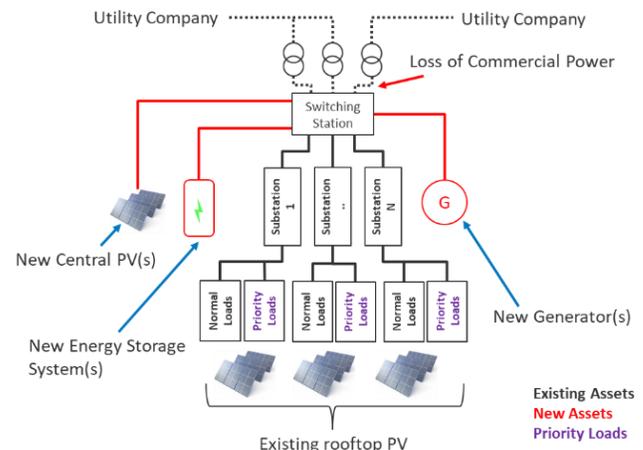


Figure 3. Conceptual design of a full base microgrid.

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*Last Updated:* October 2020



Figure 2. IESP process flow chart.



**OBJECTIVE AND SIGNIFICANCE:** Commercial aviation in Hawai'i currently uses nearly 700 million gallons of jet fuel per year, all of it is derived from petroleum. The University of Hawai'i (UH) is a member of the Federal Aviation Administration's (FAA) Aviation Sustainability Center (ASCENT) team of U.S. universities conducting research on production of sustainable aviation fuels (SAF). UH's specific objective is to conduct research that supports development of supply chains for sustainable jet fuel production in Hawai'i. Results may inform similar efforts in other tropical regions.

**BACKGROUND:** This project was initiated in October 2015 and is now continuing into its 6<sup>th</sup> year. Activities undertaken in support of SAF supply chain analysis include:

- Conducting literature review of tropical biomass feedstocks and data relevant to their behavior in conversion systems for SAF production;
- Engaging stakeholders to identify and prioritize general SAF supply chain barriers (e.g. access to capital, land availability, etc.);
- Developing geographic information system (GIS) based technical production estimates of SAF in Hawai'i;
- Developing fundamental property data on biomass resources; and
- Developing and evaluating regional supply chain scenarios for SAF production in Hawai'i.

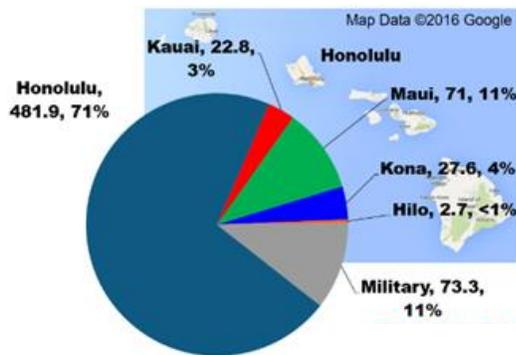


Figure 1. Commercial and military jet fuel use in 2015; Total use – 678.4M Gallons.

**PROJECT STATUS/RESULTS:** Literature reviews of both biomass feedstocks and their behavior in SAF conversion processes have been completed and published. Based on stakeholder input, barriers to SAF value chain development in Hawai'i have been identified and reported. Technical estimates of land

resources that can support agricultural and forestry-based production of SAF feedstocks have been completed using GIS analysis techniques. Samples from Honolulu's urban waste streams and candidate agricultural and forestry feedstocks have been collected and subjected to physicochemical property analyses to inform technology selection and design of SAF production facilities.

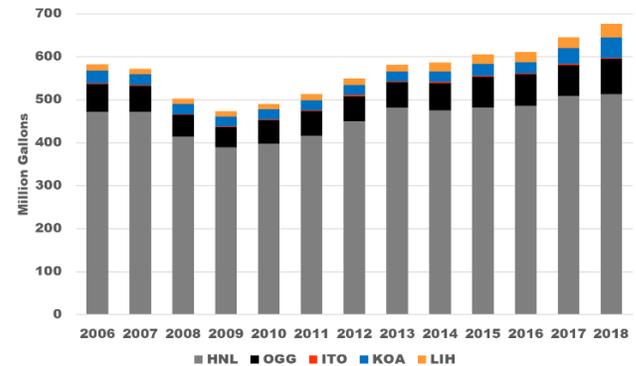


Figure 2. Commercial jet fuel consumption in Hawai'i.

### Fuel Properties of Construction and Demolition Waste Streams

A sampling and analysis campaign was undertaken to characterize fuel properties of construction and demolition waste (CDW) streams on O'ahu. As summarized in Figure 3, although the combustible fraction of the CDW have elevated ash levels compared to clean biomass materials, heating values were comparable, indicating the presence of higher energy density materials. As with most refuse derived fuels, the ash in the fuel and its composition is of particular importance, since ash impacts energy facility operations, maintenance, and emissions.

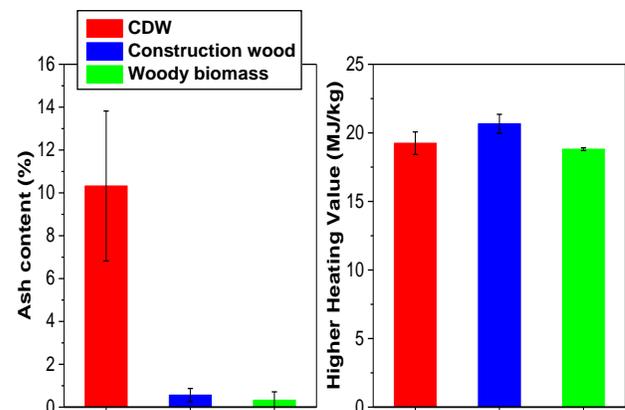


Figure 3. Ash content and heating value of the combustible fraction of CDW compared to construction wood and woody biomass.

Future work with ASCENT partners includes:

- Analysis of feedstock-conversion pathway efficiency, product slate, and maturation;
- Scoping of techno-economic analysis (TEA) issues;
- Greenhouse gas (GHG) life cycle assessment ;
- Identification of supply chain participants/partners;
- Continued stakeholder engagement;
- Acquiring transportation network and other regional data;
- Evaluating infrastructure availability; and
- Evaluating feedstock availability.

### Exploration of Biomass Feedstocks for Hawai'i

Figure 4 shows the breakdown of land use of the nearly 2 million acres of agricultural lands in Hawai'i. With the shuttering of much of the cane sugar and the pineapple industries, this total has dropped further. Bringing agricultural lands back into production can support diversification of the economy and support rural development. Biomass feedstocks for sustainable aviation fuel production are options that can contribute to this revitalization. A review of possible biomass resources and conversion technologies was performed for Hawai'i and the tropics. This review can be found at <https://dx.doi.org/10.1021/acs.energyfuels.8b03001>.

The Eco Crop model was used to complete an assessment of plant production requirements to agro-ecological attributes of agricultural lands in the State. The analysis focused on sites capable of rain fed

production to avoid using irrigated lands that could support food production. Oil seed crops, woody crops, and herbaceous crops were all considered. Ongoing work will identify underutilized agricultural areas and supply chain components necessary to develop SAF production systems.

### Evaluation of Pongamia

Of the sustainable aviation fuels currently approved by ASTM and the FAA, those based on the use of oils derived from plants and animals have the highest SAF yield and the lowest production costs. Pongamia (*Milletia pinnata*) is a tree, native to the tropics, that bears an oil seed and has plantings established on O'ahu

#### *Invasiveness Assessment*

Under this project, an observational field assessment of trees in seven locations on O'ahu was conducted by Professor Curtis Daehler (UH Dept. of Botany) to look for direct evidence of pongamia escaping from plantings and becoming an invasive weed. Although some pongamia seedlings were found in the vicinity of some pongamia plantings, particularly in wetter, partly shaded environments, almost all observed seedlings were restricted to areas directly beneath the canopy of mother trees. This finding suggests a lack of effective seed dispersal away from pongamia plantings. Based on its current behavior in the field pongamia is not invasive or established outside of cultivation on O'ahu. Because of its limited seed

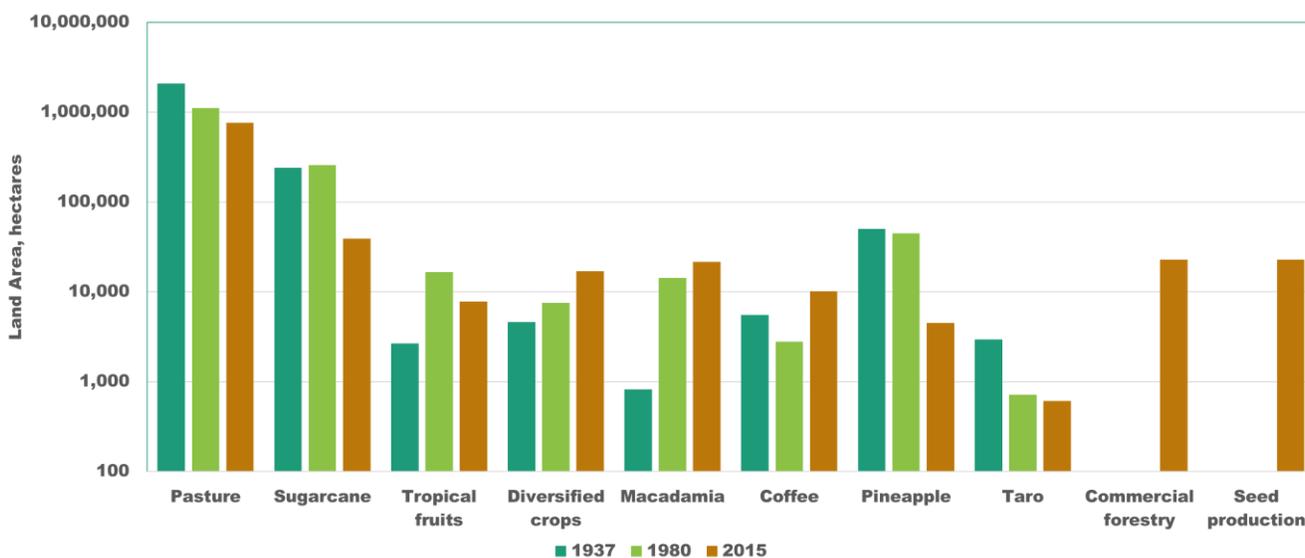


Figure 4. Breakdown of agricultural land use in Hawai'i; in 2015, approximately 100,000 acres were harvested.

dispersal and low rates of seedling establishment beyond the canopy, risk of pongamia becoming invasive can be mitigated through monitoring and targeted control of any rare escapes in the vicinity of plantings. Seeds and seed pods are water dispersed, so future risks of pongamia escape and unwanted spread would be minimized by avoiding planting at sites near flowing water, near areas exposed to tides, or on or near steep slopes. Vegetative spread by root suckers was not observed around plantings on O‘ahu, but based on reports from elsewhere, monitoring for vegetative spread around plantations is recommended; unwanted vegetative spread might become a concern in the future that could be addressed with localized mechanical or chemical control.

### Fuel properties

Pongamia is a potential resource for renewable fuels in general and sustainable aviation fuel in particular. Both pods and seeds offer pathways to fuel (Figure 5). This project characterized physicochemical properties of reproductive material (seeds and pods) from pongamia trees grown in different environments at five locations on O‘ahu. Proximate and ultimate analyses, heating value, and elemental composition of the seeds, pods, and de-oiled seed cake were determined. The oil content of the seeds and the properties of the oil were determined using American Society for Testing and Materials (ASTM) and American Oil Chemist’s Society (AOCS) methods. The seed oil content ranged from 19 to 33 % wt. across the trees and locations. Oleic (C18:1) was the fatty acid present in greatest abundance (47 to 60 % wt) and unsaturated fatty acids accounted for 77 to 83 % wt of the oil. Pongamia oil was found to have similar characteristics as other plant seed oils (canola and jatropha) and would be expected to be well suited for hydro-processed production of sustainable fuel.

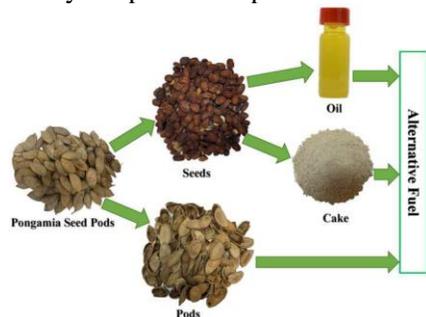


Figure 5. Pathways from Pongamia seed pods to fuel.

### Coproduct Development

Additional study was devoted coproducts development from pongamia pods. Torrefaction, a thermochemical treatment conducted in the absence of oxygen was used to reduce the oxygen content of the torrefied product compared to the parent biomass. In general, torrefaction of woody biomass materials results in mass and energy yields of 70 % and 90 %, respectively. Consequently, energy densification (mass basis) improvement by a factor of 1.3 is typical. The mass fraction of the parent biomass volatilized during torrefaction (~30%) is of low energy content, only ~10% of the total energy. Torrefied materials generally possess higher energy density, better grindability, better hydrophobicity and biological stability, which can all contribute to reducing the overall conversion cost. In addition, the torrefied biomass should have lower H/C and O/C ratio compared to the raw biomass.

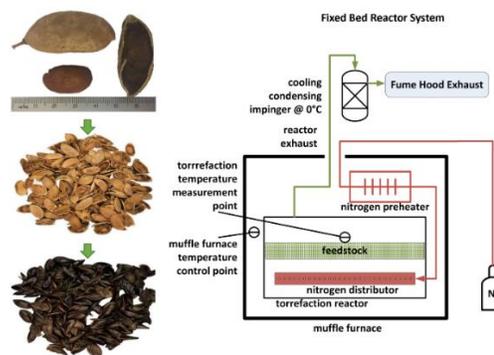


Figure 6. Laboratory scale torrefaction test bed.

*Funding Source:* Federal Aviation Administration; Energy Systems Development Special Fund

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*Last Updated:* November 2020



**OBJECTIVE AND SIGNIFICANCE:** The purpose of this project was to develop technologies to produce high-grade liquid fuel from synthesis gas derived from agricultural wastes. The drop-in liquid fuel can be directly used in modern engines of vehicles and ships without sacrifice of engine performance.

**BACKGROUND:** Agricultural wastes are underutilized renewable resource with low heating values (HHV 15-18 MJ/kg) and high oxygen contents (40-50 wt%). The composition of raw biomass varies depending on plant species and farming conditions. It is a technical challenge to convert agriculture wastes into high-grade liquid fuels that meet the fuel standards of modern engines. The biomass wastes, however, can be gasified into a synthesis gas (syngas) that contains primarily carbon monoxide (CO), hydrogen (H<sub>2</sub>) and carbon dioxide (CO<sub>2</sub>). The new technologies in development produce polyhydroxybutyrate (PHB) from the syngas by using microbial organisms and then reform the PHB polyester into gasoline-grade liquid fuel.

**PROJECT STATUS/RESULTS:** Two core technologies were investigated and developed: (a) microbial gas fermentation and (b) thermal catalytic reforming of PHB. Because of the poor solubility of gas in aqueous solution, a novel bioreactor was invented to enhance the mass transfer of gas substrates in aqueous solution by 40-200% in comparison with conventional aerated bioreactors. In addition, a continuous liquid flow operation mode of the bioreactor further increased the productivity up to 2 g/L.h, the benchmark of fuel ethanol fermentation. Under controlled conditions, the microbial cells formed a large amount of PHB (60% of cell mass) as an energy storage material. The novel bioreactor was scaled up to 200 liters for a pilot project that is in negotiation with potential industrial partners and investors.

PHB was recovered and reformed on a solid acid catalyst under mild conditions (<240 °C) to form a hydrocarbon oil. The major compounds of the PHB oil were alkanes, alkenes, and aromatics, the same compounds found in fossil gasoline and diesel. Depending on boiling points, the PHB oil was divided into a light oil (77 wt%) and a heavy oil (23 wt%). Their elemental compositions and heating values were determined and compared with commercial gasoline and biodiesel as shown in Table 1. The light oil has the same elemental composition and heating value of the gasoline obtained from a local gas station and the heavy oil is very close to a commercial biodiesel.

PHB is a polyester of 3-hydroxybutyrate (C<sub>4</sub>H<sub>5</sub>O<sub>2</sub>) and contains a substantial amount of oxygen (38% wt). Oxygen removal is essential to make hydrocarbon compounds for high heating value and desired fuel performance. The research identified the main reactions and key intermediates in the catalytic reforming of PHB. It was revealed that oxygen was removed as CO<sub>2</sub> without hydrogen consumption, a techno-economic advantage in comparing with other biofuel technologies that consume large amounts of hydrogen.

The project, now completed, has generated four reports and twelve research articles in peer-reviewed scientific journals. One invention of novel bioreactor has been disclosed and filed for global patents.

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020

Table 1. Comparison of PHB oils with commercial gasoline and biodiesel

Liquid Fuels	Gasoline	Light PHB oil	Heavy PHB oil	Biodiesel
Boiling Points (°C)	40-200	40-240	240-310	180-330
C (wt %)	80.4	81.4	79.4	77
H (wt %)	12.3	11.3	9.7	11.8
N (wt %)	0.1	0.1	0.2	-
O (wt %)	7.2	7.2	10.7	11.2
Heating Value (HHV MJ/kg)	41.8	41.4	38.4	39.7

## **ADDITIONAL PROJECT RELATED LINKS**

### **TECHNICAL REPORTS:**

1. 2019, J. Yu, [Liquid Fuels from Syngas](#), Task 3.3, in [APRISES 14 Final Technical Report](#), Office of Naval Research (ONR) Grant Award Number N00014-15-1-0028.
2. 2018, J. Yu, [Liquid Fuels from Synthesis Gas](#), Task 3.2d, in [APRISES 12 Final Technical Report](#), ONR Grant Award Number N00014-13-1-0463.
3. 2018, J. Yu, [Liquid fuels from Synthesis Gas](#), Task 3.2d, in [APRISES 13 Final Technical Report](#), ONR Grant Award Number N00014-14-1-0054.
4. 2017, J. Yu, [Biochemical Conversion of Synthesis Gas into Liquid Fuels](#), Task 3.2d, in [APRISES 11 Final Technical Report](#), ONR Grant Award Number N00014-12-1-0496.

### **PAPERS AND PROCEEDINGS:**

1. 2019, J. Yu, Y. Lu, [Carbon dioxide fixation by a hydrogen-oxidizing bacterium: Biomass yield, reversal respiratory quotient, stoichiometric equations and bioenergetics](#), Biochemical Engineering Journal, Vol. 152, Article 107369.
2. 2018, J. Yu, P. Munasinghe, [Gas Fermentation Enhancement for Chemolithotrophic Growth of Cupriavidus necator on Carbon Dioxide](#), Fermentation, Vol. 4, Issue 3, Paper 63. (Open Access: [PDF](#))
3. 2018, J. Yu, [Fixation of carbon dioxide by a hydrogen-oxidizing bacterium for value-added products](#), World Journal of Microbiology and Biotechnology, Vol. 34, Issue 7, Article 89.
4. 2017, Y. Lu, J. Yu, [Comparison analysis on the energy efficiencies and biomass yields in microbial CO<sub>2</sub> fixation](#), Process Biochemistry, Vol. 62, pp. 151-160.
5. 2017, Y. Lu, J. Yu, [Gas mass transfer with microbial CO<sub>2</sub> fixation and poly\(3-hydroxybutyrate\) synthesis in a packed bed bioreactor](#), Biochemical Engineering Journal, Vol. 122, pp. 13-21.
6. 2015, S. Kang, J. Yu, [A gasoline-grade biofuel formed from renewable polyhydroxybutyrate on solid phosphoric acid](#), Fuel, Vol. 160, pp. 282-290.
7. 2015, S. Kang, J. Yu, [Reaction routes in catalytic reforming of poly\(3-hydroxybutyrate\) into renewable hydrocarbon oil](#), RSC Advances, Vol. 5, Issue 38, pp. 30005-30013.
8. 2014, S. Kang, J. Yu, [One-pot production of hydrocarbon oil from poly\(3-hydroxybutyrate\)](#), RSC Advances, Vol. 4, Issue 28, pp. 14320-14327.

### **PRESENTATIONS:**

1. 2019, J. Yu, [Drop-in Transportation Fuels from Renewable Hydrogen and Carbon Dioxide](#), Presented at the World Hydrogen Technologies Convention, Tokyo, Japan, June 2-7.
2. 2018, J. Yu, [A Green Plastic and Drop-in Transportation Fuels from Carbon Dioxide and Renewable Energy](#), Proceeding of the TechConnect World Innovation Conference & Expo, TechConnect Briefs, Vol. 2 Materials for Energy, Efficiency and Sustainability: TechConnect Briefs, pp. 187-190.
3. 2017, J. Yu, [Drop-in Transportation Fuels from Carbon Dioxide and Solar Hydrogen](#), Presented at the Environmental and Energy Resource Management Summit, Washington, DC, November 9-11.

### **LABORATORY: [BIOPROCESSING LAB](#)**



### C3: Fuel Characterization by Multidimensional Gas Chromatography

**OBJECTIVE AND SIGNIFICANCE:** The objective of this project is to identify and characterize trace quantities of heteroatomic organic species (HOS) in aviation, maritime, and diesel fuels. New analytical methods under development can evaluate the composition of fuels currently in use and those stored as strategic reserves. The knowledge gained in this project will improve the understanding of the influences of HOS on fuel stability and guide efforts to preserve fuel quality.

**BACKGROUND:** Liquid fuels are, by nature, chemically complex. Many fit-for-purpose and stability issues are associated with trace quantities of HOS. Identification and quantitation of HOS are challenging due to their low concentration and complex composition of fuel matrix. Multidimensional gas chromatography (MDGC) typically uses sequential separations based on differences in polarity and boiling point as the basis for fuel sample analysis. The current state-of-the-art for MDGC is comprehensive two-dimensional GC (2D-GC).

HNEI began developing a fuel laboratory in 2012 and the current capabilities include standard analysis methods required by ASTM and military fuel specifications. Research conducted in the fuel laboratory has included investigating the impacts of long-term storage, oxidative conditions, contaminants, etc. of conventional and alternative fuels and their blends.

A 2D-GC was acquired in August 2018, expanding the fuel laboratory's ability to identify and quantify fuel constituents present in trace amounts ( $\leq 100$  ppm). The HNEI 2D-GC employs two injectors and three detectors (i.e. mass spectrometer, nitrogen chemiluminescence and sulfur chemiluminescence) to analyze fuel components and HOS with a single injection event. Neat fuels can be injected directly without requiring solvent dilution.

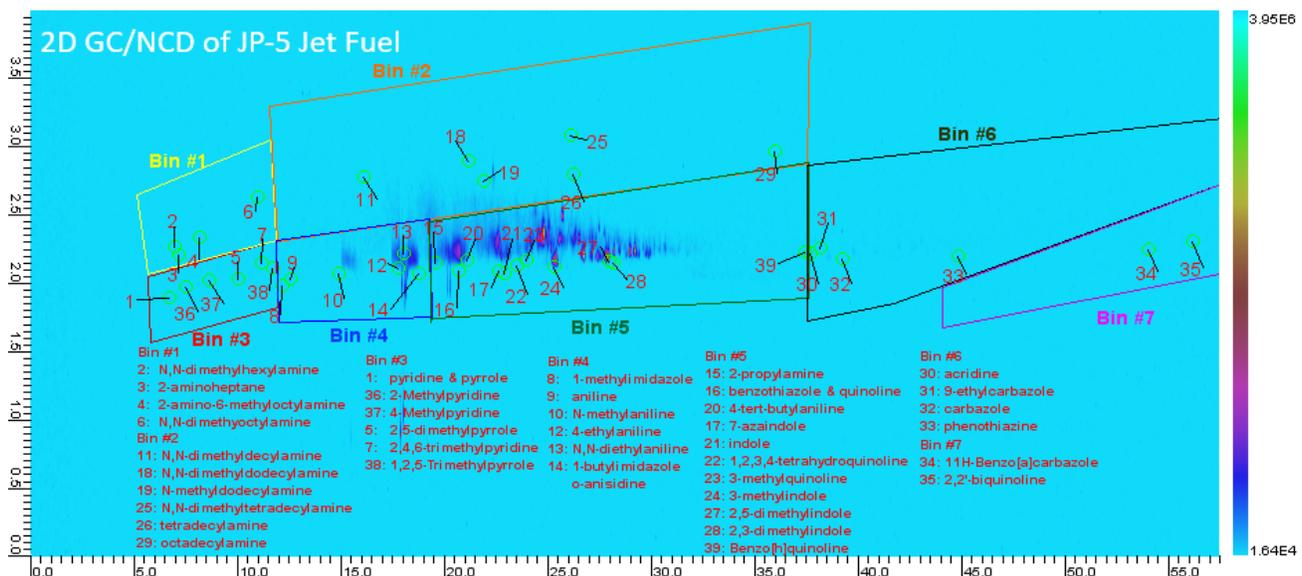
**PROJECT STATUS/RESULTS:** HNEI is currently collaborating with personnel from the U.S. Navy Fuels Cross-Functional Team on 2D-GC applications, including:

- Determining fuel hydrocarbon matrix;
- Investigating the distribution and contents of nitrogen and sulfur compounds in fuels;
- Participating in round robin tests to identify and quantify nitrogen compounds in various type of fuels;
- Exploring the relationships between fuel long-term storage and the content of antioxidant additives; and
- Utilizing HOS characterization methods to investigate the potential impacts of HOS on fuel properties and fuel stability.

*Funding Source:* Office of Naval Research

*Contact:* Scott Turn, [sturn@hawaii.edu](mailto:sturn@hawaii.edu); Jinxia Fu, [jinxiafu@hawaii.edu](mailto:jinxiafu@hawaii.edu)

*Last Updated:* October 2020





**OBJECTIVE AND SIGNIFICANCE:** The objective of this research is to improve the durability and conversion efficiency of novel *chalcopyrite* thin-film photo-absorbers for photoelectrochemical (PEC) production of *solar fuels*, aiming for a \$2/kg production cost of renewable hydrogen.

**BACKGROUND:** Sometimes referred as *Artificial Photosynthesis*, PEC technology combines advanced photovoltaic (PV) materials and catalysts into a single device that uses sunlight as the sole source of energy to split water into molecular hydrogen and oxygen. In a typical PEC setup, the solar absorber is fully immersed into an electrolyte solution and solar fuels are generated directly at its surface. Fuels produced with this method can be stored, distributed, and finally recombined in a fuel cell to generate electricity, with water as the only byproduct.

In 2014, the team at HNEI's Thin Films Laboratory teamed up with several National Laboratories (LLNL, LBNL and NREL) and mainland academic teams (Stanford, UNLV) to develop new semiconducting materials for PEC water splitting, with primary focus on *chalcopyrites*. This material class, typically identified by its most popular PV-grade alloy CuInGaSe<sub>2</sub>, provides exceptionally good candidates for PEC water splitting. A key asset of this thin-film semiconductor material class is its outstanding photo-conversion efficiency, as demonstrated with CuInGaSe<sub>2</sub>-based PV cells (>23%). In a PEC configuration, our group has demonstrated that chalcopyrite-based systems are also efficient at storing solar energy into hydrogen bonds without the need of expensive precious catalysts (Gaillard, 2013)

**PROJECT STATUS/RESULTS:** The HNEI's Thin Films Laboratory is now combining theoretical modeling with state-of-the-art materials synthesis and advanced characterization capabilities to provide

deeper understanding of *chalcopyrite*-based PEC materials and engineer high-performance devices. Our recent study demonstrates that alloying *chalcopyrites* with sulfur can improve light collection and increase their photo-conversion from 30% to 65% of the theoretical limit (Gaillard, 2019). Also, we recently demonstrated that a 3-5 nanometer thick metal oxide or sulfide layer can be used to effectively passivate *chalcopyrites* surface against photocorrosion, improving their durability from only few days to up to 6 weeks (Hellstern, 2019). Finally, we are investigating new device integration schemes involving thin-films *exfoliation* and *bonding* techniques to transfer chalcopyrite layers onto other solar absorbers to create multi-junction devices with tunable properties for efficient water splitting devices (Gaillard, 2019 presentation).

This project has produced a number of works, including the three below:

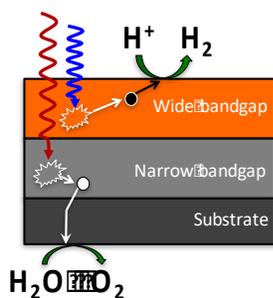
- 2019, T.R. Hellstern, et al., [Molybdenum Disulfide Catalytic Coatings via Atomic Layer Deposition for Solar Hydrogen Production from Copper Gallium Diselenide Photocathodes](#), ACS Applied Energy Materials, Vol. 2, Issue 2, pp. 1060-1066.
- 2019, N. Gaillard, [Novel Chalcopyrites For Advanced PEC Water Splitting](#), Presented at the DOE Hydrogen and Fuel Cells Program AMR and Peer Evaluation Meeting, April 30.
- 2013, N. Gaillard, et al., [Development of Chalcogenide Thin Film Materials for Photoelectrochemical Hydrogen Production](#), MRS Proceedings, Vol. 1558, Paper mrss13-1558-z02-07.

*Funding Source:* U.S. Department of Energy (EERE, HFTO)

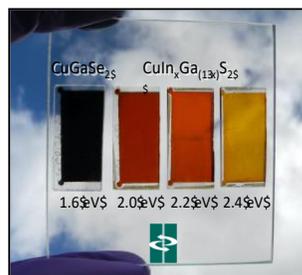
*Contact:* Nicolas Gaillard, [ngaillar@hawaii.edu](mailto:ngaillar@hawaii.edu)

*Last Updated:* October 2020

Tandem PEC device concept



Bandgap tunable photoelectrodes



Transferable PEC layers for efficient devices

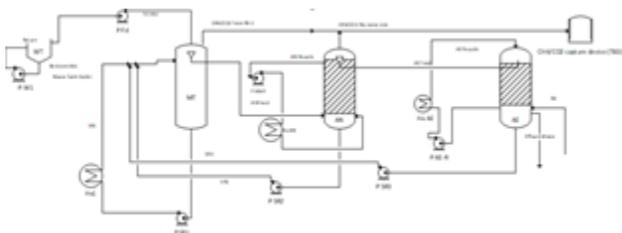




**OBJECTIVE AND SIGNIFICANCE:** To produce a master design, inclusive of PID diagrams, costing, manufacturing, and shipping to build and install a wastewater treatment system designed from past research and commercial demonstration projects. Its importance lies in its commercial scale modular-based designed. The system fits niche opportunities where concentrated wastewater streams need to be treated on-site prior to discharge to pre-existing wastewater lines. The modular nature allows non-concrete permanent installations that can be tailored to specific wastewater flows and concentration of pollutants.



**BACKGROUND:** Over a number of years, an up-flow anaerobic packed bed reactor was developed. Packed with biochar in various formulations, these reactors were verified at lab and demonstration scale to treat high and low strength wastewaters efficiently. These exercises served to verify lab generated results upon scale up to commercial size and to provide crucial insights for design revision, as well as experience for discussion with manufacturers as well as equipment selection.



From this work, PID diagrams have been constructed that have considered targeted organic loading rates and hydraulic retention times. These designs are accounting for modular fabrication of reactor units, dimensions of reactors and pipes, piping size, recycle lines, details of how to install and connect modules, utilities and electrical, materials of construction, sources of manufacturing, packing materials, shipping and installation issues, among others. Finally, cost estimates for fabrication, shipping, and installation were estimated and three-dimensional renderings were generated.

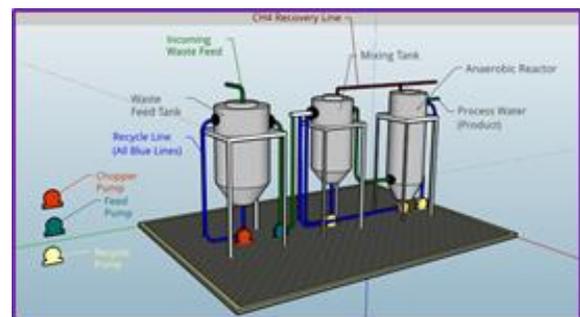


	Table 1	High Carbon Feed	Low Carbon Feed
Subsystems	Tanks/Reactor Vessels	\$126,000.00	\$126,000.00
	Pumps	\$67,742.50	\$71,000.00
	Sensors and Heaters	\$30,661.20	\$30,661.20
<b>Total</b>		<b>\$224,403.70</b>	<b>\$227,661.20</b>

**PROJECT STATUS/RESULTS:** This project has produced a number of works that can be found on the following page. The PI is seeking industrial partners to apply the system. The PI is also extending the modeling efforts to execute a cost-benefit analyses comparing WWTPs producing potable water versus reusable non-potable water. Key metrics of success are both energy use and GHG emission per unit volume water produced. Outcomes will help determine the relative choice of producing non-potable versus potable water.

*Funding Source:* Office of Naval Research

*Contact:* Michael Cooney, [mcooney@hawaii.edu](mailto:mcooney@hawaii.edu)

*Last Updated:* November 2020

## **ADDITIONAL PROJECT RELATED LINKS**

### **TECHNICAL REPORTS:**

1. 2014, M.J. Cooney, [Anaerobic Digestion of Primary Sewage Effluent](#), Report produced for the [Hawai'i Energy Sustainability Program \(HESP\)](#), under U.S. Department of Energy Grant Award DE-EE0003507.

### **PAPERS AND PROCEEDINGS:**

1. 2020, S. Lin, K. Rong, K.M. Lamichhane, R.W. Babcock, M. Kirs, M.J. Cooney, [Anaerobic-aerobic biofilm-based digestion of chemical contaminants of emerging concern \(CEC\) and pathogen indicator organisms in synthetic wastewater](#), Bioresource Technology, Vol. 299, Paper 122554.
2. 2019, M.J. Cooney, K. Rong, K.M. Lamichhane, [Cross comparative analysis of liquid phase anaerobic digestion](#), Journal of Water Process Engineering, Vol. 29, Article 100765.
3. 2017, K.M. Lamichhane, K. Lewis, K. Rong, R.W. Babcock Jr., M.J. Cooney, [Treatment of high strength acidic wastewater using passive pH control](#), Journal of Water Process Engineering, Vol. 18, pp. 198-201.
4. 2017, K.M. Lamichhane, D. Furukawa, M.J. Cooney, [Co-Digestion of Glycerol with Municipal Wastewater](#), Chemical Engineering & Process Techniques, Vol. 3, Issue 1, Paper 1034.
5. 2016, M.J. Cooney, K. Lewis, K. Harris, Q. Zhang, T. Yan, [Start up performance of biochar packed bed anaerobic digesters](#), Journal of Water Process Engineering, Vol. 9, pp. e7-e13.
6. 2014, R.J. Lopez, S.R. Higgins, E. Pagaling, T. Yan, M.J. Cooney, [High rate anaerobic digestion of wastewater separated from grease trap waste](#), Renewable Energy, Vol. 62, pp. 234-242.

### **PRESENTATIONS:**

1. 2014, M.J. Cooney, [Low Energy High Rate Anaerobic – Aerobic Digestion \(HRAAD\) and Applications](#), Presented at the ECS MA2014-02 Meeting, Cancun, Mexico, October 5-9, Abstract 2288.



**OBJECTIVES AND SIGNIFICANCE:** Methane hydrates in deep ocean sediments and arctic permafrost constitute an enormous energy reservoir that is estimated to exceed the energy content of all known coal, oil, and conventional natural gas resources. The primary goals of this project that has been ongoing since 2001 are to 1) support exploration of hydrate reservoirs in seafloor sediments and arctic permafrost; 2) support the development of safe and practicable methods to destabilize hydrates to produce methane fuel; and 3) advance our understanding of the environmental impacts of natural seeps and accidental releases of methane and other hydrocarbons in the ocean. HNEI has also investigated engineering applications of hydrates including desalination and H<sub>2</sub> storage, and promoted many international R&D collaborations.

**BACKGROUND:** Research on CO<sub>2</sub> hydrates at HNEI began in the 1990's as part of an international collaboration on CO<sub>2</sub> ocean sequestration. The research scope was expanded to include methane hydrates when HNEI was asked by the Minerals Management Service (MMS) of the Department of the Interior to participate in a study on deep oil spills. Over time, we have conducted a host of laboratory investigations on a wide range of topics related to hydrates and participated in numerous oceanographic research cruises to offshore hydrate zones.

At present, our activities are focused on the following three areas: 1) chemical destabilization of hydrates; 2) biogeochemistry of seafloor methane hydrates; and 3) the biodegradation of methane in the ocean.

Methane hydrates can be destabilized by application of heat, depressurization, or contact with chemical reagents known as thermodynamic inhibitors. Destabilization results in melting of the solid hydrate, which releases liquid water and methane gas. Many conventional inhibitors are expensive and/or toxic. Our laboratory experiments evaluate the effectiveness of various inhibitors with the goal of identifying safe and inexpensive alternatives. Figure 1 shows a novel facility developed by HNEI researchers to investigate the thermochemistry of hydrates. This facility employs a fiberoptic probe coupled into a high pressure calorimetry test cell to permit Raman spectra to be sampled as hydrates form and decompose. The

Raman calorimeter has provided valuable data to assess inhibitor effectiveness.



Figure 1. Photo of the Raman calorimetry facility.

**PROJECT STATUS/RESULTS:** Experimental work under this project is nearing completion. Key results of recent work include: analysis of seismic data of hydrate reservoirs in the Nankai Trough offshore of Japan and determination of the effectiveness of alternative inhibitors such as salts that occur naturally in seawater and glycerol to dissociate hydrates. An investigation of methane hydrate kinetics within a sand substrate is nearing completion.

This project has produced the following publications:

- 2017, J.T. Weissman, et al., [Hydrogen Storage Capacity of Tetrahydrofuran and Tetra-N-Butylammonium Bromide Hydrates Under Favorable Thermodynamic Conditions](#), *Energies*, Vol. 10, Issue 8, Paper 1225.
- 2017, K. Taladay, et al., [Gas-In-Place Estimate for Potential Gas Hydrate Concentrated Zone in the Kumano Basin, Nankai Trough Forearc, Japan](#), *Energies*, Vol. 10, Issue 10, Paper 1552.
- 2016, T.Y. Sylva, et al., [Inhibiting Effects of Transition Metal Salts on Methane Hydrate Stability](#), *Chemical Engineering Science*, Vol. 155, pp. 10-15.
- 2016, T.H. Ching, et al., [Biodegradation of biodiesel and microbiologically induced corrosion of 1018 steel by Moniliella wahieum Y12](#), *International Biodeterioration & Biodegradation*, Vol. 108, pp. 122-126.

*Funding Source:* Office of Naval Research

*Contact:* Brandon Yoza, [byoza@hawaii.edu](mailto:byoza@hawaii.edu)

*Last Updated:* October 2020



**OBJECTIVE AND SIGNIFICANCE:** The primary objectives of this study are to identify aquatic microbes that effectively degrade hydrocarbon pollutants in estuaries and the ocean, and to elucidate the mechanisms of this degradation. This information is vital to understand and assess the extent of the environment impacts of oil and gas discharges and to develop novel strategies to mitigate these impacts.

**BACKGROUND:** This project is an adjunct to the APRISES Methane Hydrates task. Purposeful (e.g., for natural gas recovery) or accidental destabilization of seafloor hydrates will release methane into the oceanic water column. In addition, many commercial and DoD activities result in hydrocarbon contamination of the ocean and estuarine environments. Under these types of scenarios, bacterial and fungal communities in the water are known to play a key role in ameliorating the impacts of the polluting hydrocarbons species.

Laboratory experiments have been conducted to identify microbes that can metabolize and remove hydrocarbon contaminants from aquatic environments and to investigate the key pathways and mechanisms of this process. Figure 1 is a microscope photograph of a species of fungus found in Hawai'i that can degrade hydrocarbons, which was isolated and identified in this study.

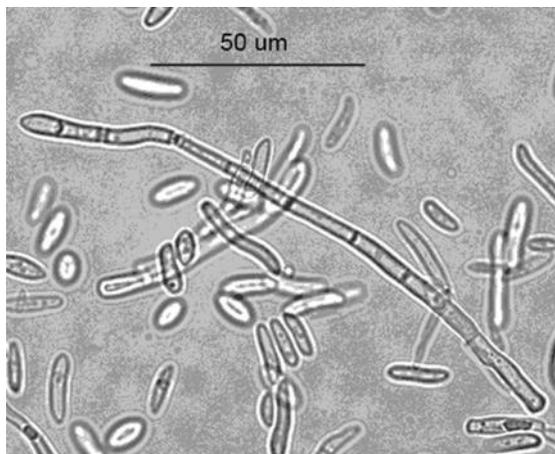


Figure 1. *Moniliella wahieum* (ATCC MYA-4962) a hydrocarbon degrading fungus that has been isolated and characterized in Hawai'i.

**PROJECT STATUS/RESULTS:** This project is ongoing. Recent results are available in the following peer-reviewed publications:

1. 2020, J. Liang, et al., [Rapid granulation using CaSO<sub>4</sub> and polymers for refractory wastewater treatment in up-flow anaerobic sludge blanket reactor](#), *Bioresource Technology*, Vol. 305, Paper 123084.
2. 2018, Q. Wang, et al., [Treatment of petroleum wastewater using an up-flow anaerobic sludge blanket \(UASB\) reactor and turf soil as a support material](#), *Journal of Chemical Technology and Biotechnology*, Vol. 93, Issue 11, pp. 3317-3325.
3. 2017, C. Ye, et al., [Cometabolic degradation of blended biodiesel by \*Moniliella wahieum\* Y12T and \*Byssoschlamys nivea\* M1](#), *International Biodeterioration & Biodegradation*, Vol. 125, pp. 166-169.
4. 2016, C-M. Chen, et al., [Laboratory studies of rice bran as a carbon source to stimulate indigenous microorganisms in oil reservoirs](#), *Petroleum Science*, Vol. 13, Issue 3, pp. 572-583.
5. 2016, T.H. Ching, et al., [Biodegradation of biodiesel and microbiologically induced corrosion of 1018 steel by \*Moniliella wahieum\* Y12](#), *International Biodeterioration & Biodegradation*, Vol. 108, pp. 122-126.
6. 2013, R.B. Coffin, et al., [Spatial variation in shallow sediment methane sources and cycling on the Alaskan Beaufort Sea Shelf/Slope](#), *Marine and Petroleum Geology*, Vol. 45, pp. 186-197.
7. 2013, R.M. Harada, et al., [Diversity of Archaea communities within contaminated sand samples from Johnston Atoll](#), *Bioremediation Journal*, Vol. 17, Issue 3, pp. 182-189.

*Funding Source:* Office of Naval Research

*Contact:* Brandon Yoza, [byoza@hawaii.edu](mailto:byoza@hawaii.edu)

*Last Updated:* October 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix D: Electrochemical Power Systems

### D1: Fuel Cell Development for Electric Powered Unmanned Aerial Vehicles

**OBJECTIVE AND SIGNIFICANCE:** Fuel cells offer the opportunity to significantly increase the flight duration of electric powered unmanned aerial vehicles (UAVs). With fuel cell power systems, increases of 5-10x in flight duration are possible for the same volume and weight constraints as high energy lithium batteries. Under this task, HNEI continued support to the Naval Research Laboratory's (NRL) efforts to develop lightweight, high efficiency fuel cell systems for UAVs.

**BACKGROUND:** Electric propulsion offers several advantages over small hydrocarbon powered engines, i.e. near silent operation, instant starting, increased reliability, easier power control, reduced thermal signature, reduced vibration, and no electric generators. A partnership between HNEI and NRL was established in 2009 to aid in NRL's development of the IonTiger UAV using a fuel cell made by an outside vendor. HNEI contributed to the program with testing and evaluation of the fuel cell system and components as well as determining effects of high altitude operations on the durability of the fuel cell. This NRL program resulted in an unofficial world-record fuel cell powered UAV flight of 26 hours on compressed hydrogen, and later 48 hours using an NRL-developed, cryogenic hydrogen storage system.



Figure 1. NRL IonTiger in flight and 550W fuel cell (insert).

Subsequently, NRL has been developing their own proprietary fuel cells and systems for UAV applications. HNEI has supported this effort via diagnostic testing, evaluation of needs, and design recommendations.

At the core of HNEI's capabilities is a configurable stack test station that can test fuel cell stacks up to 5kW and has the flexibility to adapt to new technologies. For this work, a helium leak station was built to evaluate the integrity of new seal designs and to locate and quantify leak rates. A suite of auxiliary equipment was also developed to evaluate cell to cell uniformity leading to design recommendations for new generations of NRL stack technology. HNEI also has developed a Hardware-in-the-Loop stack test station to support balance-of-plant system development and evaluate the dynamic capabilities of NRL stack technology. HNEI engineers have developed numerous stack testing protocols for NRL including initial break-in, build verification, durability, and failure diagnostic protocols.

In addition to the testing support, HNEI has also contributed to the system hardware development. For example, HNEI designed and reduced to practice a hydrogen recovery unit for the NRL fuel cell system to increase hydrogen utilization to greater than 99% with reduced weight and volume.

**PROJECT STATUS/RESULTS:** This work has resulted in publications and one patent application filed for "Hydrogen Fuel Cell Power Source with Metal Bipolar Plates". For additional information refer to the publication listing on the HNEI website or use the contact listed below.

*Funding Source:* Office of Naval Research

*Contact:* Keith Bethune, [bethune@hawaii.edu](mailto:bethune@hawaii.edu)

*Last Updated:* October 2020

## **ADDITIONAL PROJECT RELATED LINKS**

### **TECHNICAL REPORTS:**

1. 2019, K. Bethune, [Support to NRL](#), subsection of Task 2.1 Fuel Cell Testing, in [APRISES 14 Final Technical Report](#), Office of Naval Research Grant Award Number N00014-15-1-0028.
2. 2018, K. Bethune, [Support to NRL](#), subsection of Task 2.1a Fuel Cell Development, in [APRISES 12 Final Technical Report](#), Office of Naval Research Grant Award Number N00014-13-1-0463.
3. 2018, K. Bethune, [NRL Support](#), subsection of Task 2.1 Fuel Cell Development, Testing and Modeling, in [APRISES 13 Final Technical Report](#), Office of Naval Research Grant Award Number N00014-14-1-0054.

### **PAPERS AND PROCEEDINGS:**

1. 2020, Y. Garsany, C.H. Bancroft, R.W. Atkinson III, K. Bethune, B.D. Gould, K.E. Swider-Lyons, [Effect of GDM Pairing on PEMFC Performance in Flow-Through and Dead-Ended Anode Mode](#), *Molecules*, Vol. 25, Issue 6, Paper 1469. (Open Access: [PDF](#))
2. 2015, B.D. Gould, J.A. Rodgers, M. Schuette, K. Bethune, S. Louis, R. Rocheleau, K. Swider-Lyons, [Performance and Limitations of 3D-Printed Bipolar Plates in Fuel Cells](#), *ECS Journal of Solid State Science and Technology*, Vol. 4, Issue 4, pp. P3063-P3068. (Open Access: [PDF](#))

### **PRESENTATIONS:**

1. 2020, Y. Garsany, C.H. Bancroft, R.W. Atkinson, K. Bethune, B.D. Gould, K. Swider-Lyons, [Operation of PEMFC Anodes in Dead-Ended Vs. Flow-through Modes](#), Presented at the ECS 2020-02 Meeting, Honolulu, Hawai'i, October 4-9, Abstract 2212.
2. 2019, R.W. Atkinson, Y. Garsany, K. Bethune, J. St-Pierre, B.D. Gould, K. Swider-Lyons, [Pairing Asymmetric Gas Diffusion Media for High-Power Fuel Cell Operation](#), Presented at the ECS 2019-02 Meeting, Atlanta, Georgia, October 13-17, Abstract 1428.
3. 2019, Y. Garsany, R.W. Atkinson, K. Bethune, J. St-Pierre, B.D. Gould, K. Swider-Lyons, [Cathode Catalyst Layer Design with Graded Porous Structure for Proton Exchange Membrane Fuel Cells](#), Presented at the ECS 2019-02 Meeting, Atlanta, Georgia, October 13-17, Abstract 1423.



**OBJECTIVE AND SIGNIFICANCE:** The objective of this project was to develop effective methods to restore the performance loss caused by air contaminants in proton exchange membrane fuel cell (PEMFC) systems, especially those that are restored by interrupting the contaminant exposure. An effective recovery method would slow down the degradations of membrane electrodes assembly components and their performances, facilitate the system meeting with the U.S. DOE technical targets for PEMFC performance and durability, and overcome the air pollution challenges to the applications of PEMFC systems.

**BACKGROUND:** PEMFC is considered a promising clean energy technology for transportation and stationary applications. Currently, Pt-based catalysts are still extensively applied in PEMFC due to the high electrochemical activity. Unfortunately, more than 200 airborne pollutants can be introduced into the PEMFC cathode via the air stream. Air pollution is a challenge for the PEMFC application.

In past decades, many contaminants were studied with single cells or stacks using both accelerated and long-term tests. At HNEI, more than twenty potential contaminants have been studied in single cell configurations. Most of these compounds adsorb and react on Pt surface and compete with oxygen reduction reaction, a key reaction in PEMFC. Fortunately, the effects from both unsaturated hydrocarbon and oxygen-containing hydrocarbon contaminants, could be mitigated by neat air operation. However, for sulfur and halogen compounds, the cell performance suffers a significant loss and does not recover with the neat air operation. The contamination also accelerates the permanent degradation of Pt catalysts and electrolyte membrane. The contamination mechanisms of those compounds, i.e. bromomethane, are illustrated in Figure 1. The contaminants permeate through the thin ionomer film and break down to adsorbates ( $\text{BrCH}_3$  to  $\text{Br}^-$ ,  $\text{SO}_2$  to S and  $\text{SO}_4^{2-}$ ) on the Pt catalyst surface. The adsorbates cannot be oxidized or desorbed under normal PEMFC operating conditions, and accumulate at the catalyst layer interface. The anions even cannot be removed by cyclic voltammetry scanning alone due to Donnan exclusion by the ionomer. The catalyst surface then loses activities to the fuel cell reactions. For a long-term operation, the absorption of anions also causes

permanent damages on the MEA, such as Pt dissolution and particle growth, and ionomer electrolyte decomposition.

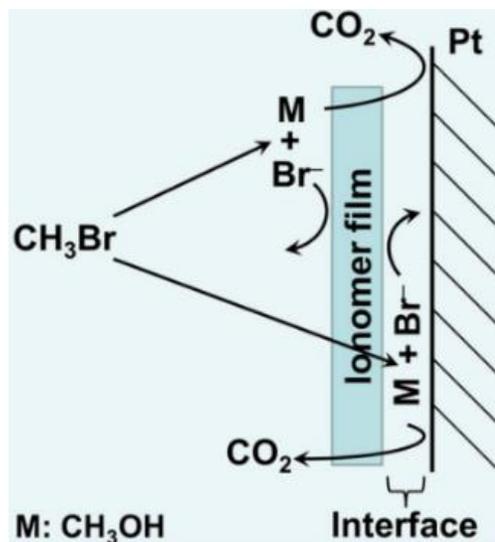


Figure 1. Contamination mechanisms of bromomethane in PEMFC cathode.

The possible solutions that have been proposed includes restoring the cell performance by in-situ potential scanning after the contamination and eliminating the contaminants with filter before reaching to the catalyst layer. However, the potential scanning is not applicable to stacks because the control of every cathode potential is required for multiplying electrical connections and equipment needs. On the other hand, chemical filter typically only last several months under realistic PEMFC vehicle operations.

**PROJECT STATUS/RESULTS:** Under this project, a performance recovery method has been developed by HNEI that incorporates a combination of gas purging and water flushing operations. Specific procedures are based on a comprehensive understanding on the contamination mechanisms of the selected air pollutant. The method, validated using single cells, was shown to restore the performance losses and remove the adsorbates and anions after poisoning with bromomethane, hydrogen chloride, or sulfur dioxide. Representative results are shown in Figures 2 and 3. The cell performance was restored to 100%, 97% and 99% of its initial value, respectively for those contaminants.

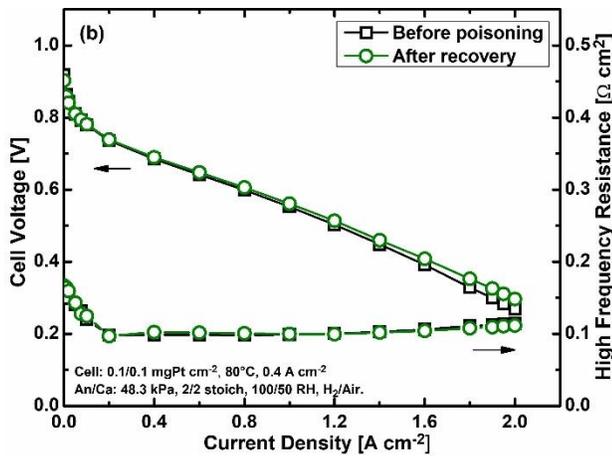
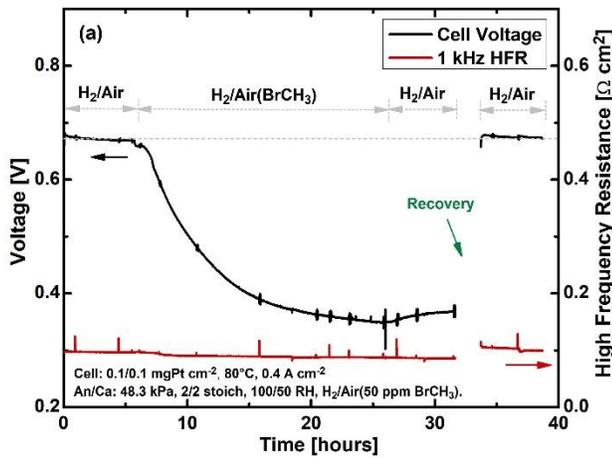


Figure 2. (a) Cell performance responses to the bromomethane contamination and recovery; (b) Cell polarization curves before poisoning and after recovery.

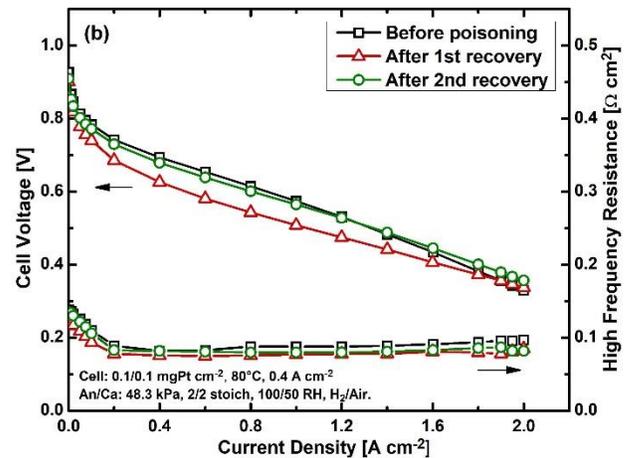
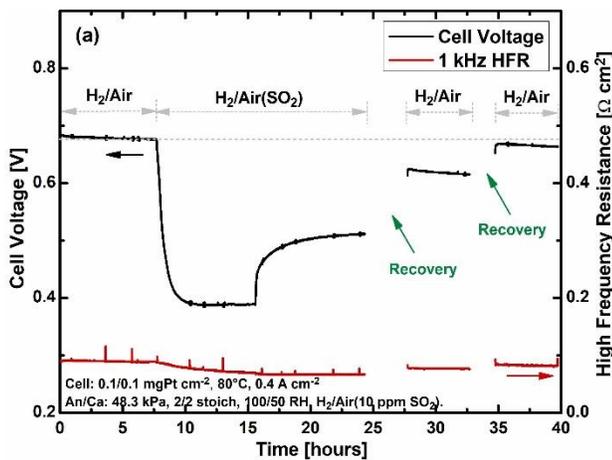


Figure 3. (a) Cell performance responses to the sulfur dioxide contamination and recovery; (b) Cell polarization curves before poisoning and after recovery.

In summary, an effective recovery method has been developed and demonstrated that yields an almost complete performance recovery after poisoning with bromomethane, hydrogen chloride, or sulfur dioxide. A provisional patent was filed. Collaboration with the PEMFC stacks manufacturers, who are running fuel cell vehicle demonstrations, is being sought for further validating the efficiency of the recovery method for contaminated PEMFC stacks.

*Funding Source:* Office of Naval Research; U.S. Department of Energy

*Contact:* Yunfeng Zhai, [yunfeng@hawaii.edu](mailto:yunfeng@hawaii.edu); Jean St-Pierre, [jsp7@hawaii.edu](mailto:jsp7@hawaii.edu)

*Last Updated:* October 2020



**OBJECTIVE AND SIGNIFICANCE:** The goals of this project are evaluation of the performance of anion exchange membrane fuel cells (AEMFCs) with low platinum group metal (PGM) content and PGM-free cathode catalysts under various operating conditions and advance understanding of effects of membrane electrode assemblies (MEAs) components on mass transport and water management.

**BACKGROUND:** The strongest motivation factor that has driven interest in AEMFCs technology (Figure 1) is the possibility of eliminating Pt catalysts from anode and cathode, since intrinsic catalytic activity towards oxygen reduction is higher in alkaline media for PGM-free materials than for Pt-based catalysts.

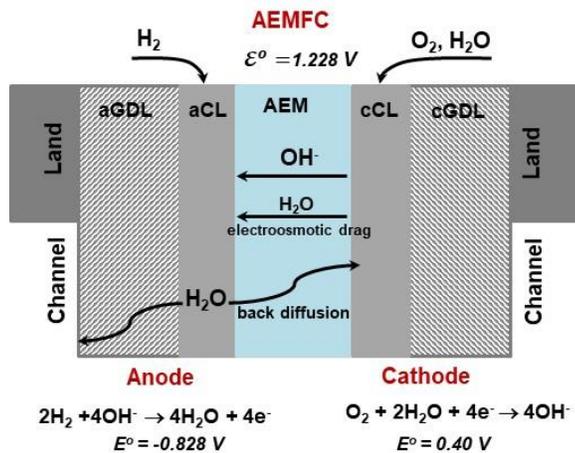


Figure 1. Schematic representation of AEMFC.

The next logical step will be integration of Pt and PGM-free catalysts to the AEMFC MEA. However, well-established technologies of manufacturing of proton exchange membrane fuel cell (PEMFC) MEAs cannot be directly transferred into the field of AEMFCs. The main reasons for getting lower power output are inability to create properly structured electrodes with sufficient mass transport, porosity, electronic conductivity, and catalyst layer (CL) thickness. The performance can be improved by advanced design of the electrode layers and adequate choice of gas diffusion layers (GDLs) for better water management.

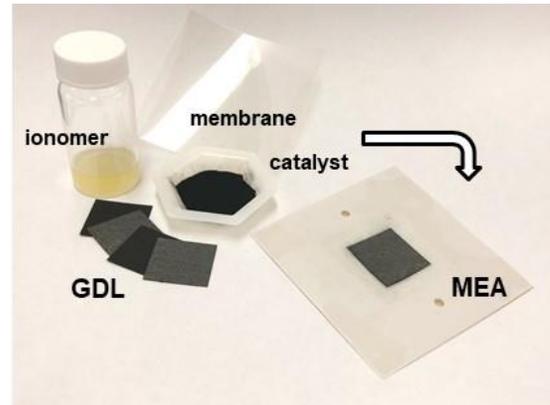


Figure 2. Materials for manufacturing of AEMFC MEAs: ionomer solution, membrane, GDLs, and catalyst.

**PROJECT STATUS/RESULTS:** The project was initiated in 2020 and the current accomplishments include:

- The first anion exchange MEA samples with Pt-based electrodes were assembled.
- A break-in/start-up procedure was established after discussion with AEM manufactures and successfully tested.
- Performance of the AEM MEAs was evaluated in an H<sub>2</sub>/O<sub>2</sub> gas configuration, 150 kPa back pressure and 80°C using polarization curves and electrochemical impedance spectroscopy (EIS).
- Variation of fuel and oxidant humidification demonstrated that maximum power density of 750 mW cm<sup>-2</sup> was achieved at reduced anode (50%) and full cathode (100%) gas humidification.

Future work will include a continuation of electrochemical studies of AEMFCs using available methods and techniques.

*Funding Source:* Office of Naval Research

*Contact:* Tatyana Reshetenko, [tatyanar@hawaii.edu](mailto:tatyanar@hawaii.edu)

*Last Updated:* October 2020



**OBJECTIVE AND SIGNIFICANCE:** Development of platinum group metal free (PGM-free) catalyst for electrochemical oxygen reduction offers a potential to reduce the production cost of proton exchange membrane fuel cells (PEMFC). Under this project, we are developing highly active PGM-free catalysts and optimizing their incorporation into a fuel cell.

**BACKGROUND:** Today's PEMFC commercial energy generated systems are typically utilizing Pt-based catalysts for hydrogen oxidation and oxygen reduction reactions at anode and cathode, respectively. The substitution of oxygen reduction Pt catalysts by PGM-free materials delivers not only lower manufacturing cost (less than or equal to \$3/kW), but also ensures independence from Pt and other precious metal availability. In addition, application of PGM-free catalysts at the cathode provides tolerance to airborne contaminants ( $\text{NO}_2$ ,  $\text{SO}_2$ ), which typically seriously affect Pt-based PEMFC performance.

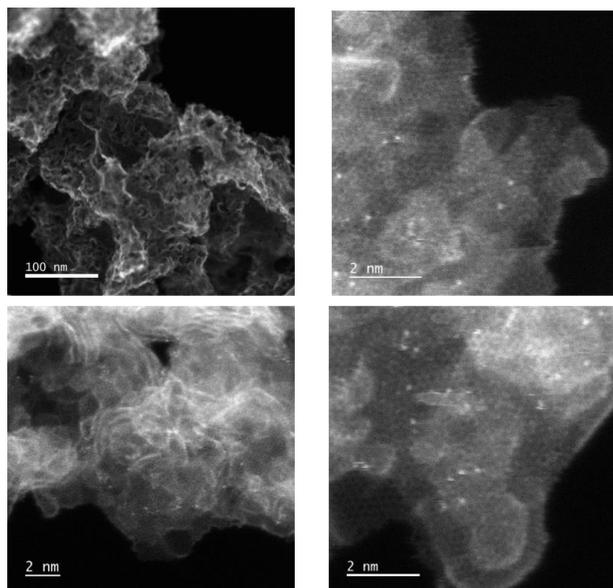


Figure 1. SEM and HRTEM images of 3<sup>rd</sup> generation of Fe-N-C catalysts. The catalyst design resulted in atomically dispersed Fe-N<sub>x</sub> active centers (bright dots at TEM images).

PGM-free catalysts consist of non-precious transition metal (Fe, Co, Mn) coordinated by nitrogen inside a matrix of graphitic carbon and can be inexpensively manufactured at scale. These catalysts possess high intrinsic activity for oxygen reduction measured in

electrochemical half-cell configuration. However, PGM-free electrocatalysts integrated in membrane electrode assembly (MEA) have underperformed compared to Pt based fuel cells. The performance can be improved by synergistic efforts of materials design, fine tuning of the electrode layer and comprehensive electrochemical analysis.

This project is a collaboration between industry (Pajarito Powder LLC, IRD Fuel Cell) and academia (HNEI) under a U.S. DOE funded project "Active and durable PGM-free cathodic electrocatalysts for fuel cell application" (DE-EE0008419). HNEI is conducting electrochemical evaluation of the PGM-free PEMFCs using advanced and proven electrochemical techniques.

#### **PROJECT STATUS/RESULTS:**

- Three generations of PGM-free electrocatalysts were synthesized using rationally selected precursors and conditions. Figure 1 shows SEM images of a catalyst from 3<sup>rd</sup> generation.
- The electrocatalysts were successfully integrated into electrode structures applying various ionomers and additives and using different layer designs.
- Established testing protocol for PGM-free PEMFCs which includes measurements of polarization curves, impedance spectroscopy, and cyclic voltammetry.
- Evaluated performance of 50 different MEAs. Achieved Go-no-Go target of 22-27 mA cm<sup>-2</sup> at 0.9 V.

Future work will include a continuation of electrochemical studies of catalysts and electrode designs using available methods and techniques.

*Funding Source:* U.S. Department of Energy; Office of Naval Research; Energy Systems Development Special Fund

*Contact:* Tatyana Reshetenko, [tatyanar@hawaii.edu](mailto:tatyanar@hawaii.edu)

*Last Updated:* October 2020

## **ADDITIONAL PROJECT RELATED LINKS**

### **PAPERS AND PROCEEDINGS:**

1. 2020, T. Reshetenko, A. Serov, M. Odgaard, G. Randolph, L. Osmierie, A. Kulikovsky, [Electron and proton conductivity of Fe-N-C cathodes for PEM fuel cells: A model-based electrochemical impedance spectroscopy measurement](#), Electrochemistry Communications, Vol. 118, Paper 106795. (Open Access: [PDF](#))
2. 2020, T. Reshetenko, G. Randolph, M. Odgaard, B. Zulevi, A. Serov, A. Kulikovsky, [The Effect of Proton Conductivity of Fe-N-C-Based Cathode on PEM Fuel cell Performance](#), Journal of the Electrochemical Society, Vol. 167, Issue 8, Paper 084501. (Open Access: [PDF](#))
3. 2019, T. Reshetenko, A. Serov, A. Kulikovsky, P. Atanassov, [Impedance Spectroscopy Characterization of PEM Fuel Cells with Fe-N-C-Based Cathodes](#), Journal of the Electrochemical Society, Vol. 166, Issue 10, pp. F653-660. (Open Access: [PDF](#))

### **PRESENTATIONS:**

1. 2020, T. Reshetenko, G. Randolph, M. Odgaard, B. Zulevi, A. Serov, A. Kulikovsky, [Effects of cathode proton conductivity on PGM-free PEM fuel cell performance](#), Presented at the ECS 2020-02 Meeting, Honolulu, Hawai'i, October 4-9, Abstract 2686.
2. 2019, T. Reshetenko, A. Serov, A. Kulikovsky, P. Atanassov, [Comprehensive Characterization of PGM-Free PEM Fuel Cells Using AC and DC Methods](#), Presented at the ECS 2019-02 Meeting, Atlanta, Georgia, October 13-17, Abstract 1617.
3. 2019, A. Serov, G. McCool, H. Romero, S. McKinney, A. Lubers, M. Odgaard, T.V. Reshetenko, B. Zulevi, [PGM-Free Oxygen Reduction Reaction Electrocatalyst: From the Design to Manufacturing](#), Presented at the ECS 2019-01 Meeting, Dallas, Texas, May 26-30, Abstract 1487.



**OBJECTIVE AND SIGNIFICANCE:** The objective of this project is to develop transition metal carbide catalysts for electrochemical applications. These carbide catalysts have the potential to improve the performance of a variety of electrochemical devices including fuel cells, water electrolyzers, and vanadium redox flow batteries.

**BACKGROUND:** The commercial application of a number of electrochemical technologies would benefit from the availability of low cost, efficient, and durable catalysts. Pt-group metals-based catalysts are used in most commercially available fuel cells and water electrolyzers. Unfortunately, they have the shortcomings of high cost, low earth abundance, and limited lifetime. Vanadium redox flow batteries (VRFBs) have recently attracted considerable attention for large-scale energy storage. Graphite or carbon materials have been the most common catalysts for VRFBs. However, they often show limited activity and reversibility. Transition metal carbides are regarded as attractive candidates because they possess an electronic structure similar to Pt which promotes high activities, good electronic conductivity, low cost, high abundance, and outstanding thermal and chemical stabilities. The catalytic properties of carbide catalysts strongly depend on their surface structure and composition, which are closely associated with their synthesis methods.

**PROJECT STATUS/RESULTS:** The research team at HNEI is currently focused on the synthesis of carbide catalysts for VRFBs. Rather than applying the conventional carbide synthesis method by carburization of metal precursor with hydrogen as reducing agent and carbonaceous gas (e.g.  $\text{CH}_4$ ) as carbon source, this work is exploring in-situ carburization of metal precursor with carbon material as carbon source and support without using any gaseous carbon source (Figure 1). This simple synthesis method avoids the use of environmentally unfriendly and flammable gases which are potential safety hazards in the operation. In addition, the use of carbon material as carbon source and support favors the formation of nano-sized carbides that are expected to possess a large specific surface area. Vanadium carbide supported on Vulcan XC72 ( $\text{VC}_{\text{XC72}}$ ) shows uniform distribution (Figure 2) and smaller particle size ( $\sim 32\text{nm}$ ) than on graphite ( $\text{VC}_{\text{graphite}}$ ,  $\sim 44\text{nm}$ ) and

carbon obtained from the carbonization of coconut husk ( $\text{VC}_{\text{coconut}}$ ,  $\sim 41\text{nm}$ ). Vanadium carbides exhibit significantly better catalytic activities and enhanced reversibility toward the negative electrode reactions for VRFBs than graphite which is the incumbent catalyst for VRFBs (Figure 3). The use of vanadium carbide catalysts for VRFBs has not yet been reported in the literature.

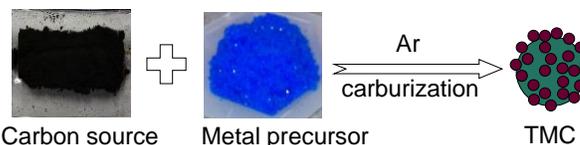


Figure 1. Schematic representation of the synthesis process for transition metal carbides.

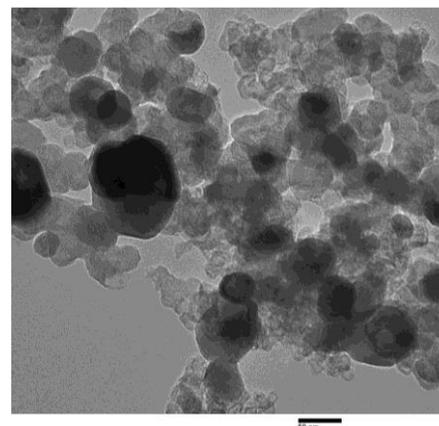


Figure 2. Transmission electron microscopy image of vanadium carbide on Vulcan XC72.

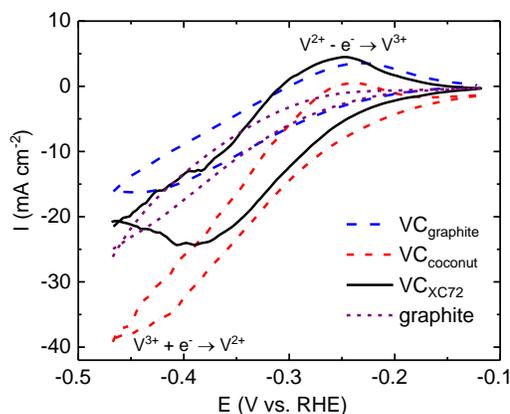


Figure 3. Cyclic voltammograms on vanadium carbides at  $5\text{mV s}^{-1}$  in  $\text{N}_2$  saturated  $3\text{M H}_2\text{SO}_4 + 1\text{M (V}^{2+} + \text{V}^{3+})$  at  $25^\circ\text{C}$ .

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix D: Electrochemical Power Systems

### D6: Battery Energy Storage Systems Durability and Reliability

**OBJECTIVE AND SIGNIFICANCE:** The objective of this work is to better understand the degradation of batteries in grid deployed systems. The knowledge gained in this project will inform best practices to improve durability and safety of large batteries deployed on the electric grid.

**BACKGROUND:** Battery Energy Storage Systems (BESS) show promise in mitigating many of the effects of high penetration of variable renewable generation. HNEI has initiated an integrated research, testing, and evaluation program to assess the benefits and durability of grid-scale BESS for various ancillary service applications. BESS were deployed at 3 sites. The first one was deployed in December 2012 on the Big Island of Hawai'i. The other two were deployed on Moloka'i and O'ahu in 2016 (Appendix B1). Usage was closely monitored and maintenance cycles using protocols recommended by the manufacturer, as well as custom HNEI protocols, were applied.

**PROJECT STATUS/RESULTS:** Usage from the BESS was carefully analyzed to facilitate laboratory testing of individual cells representative of actual operating conditions.

All cells used in the demonstrations and laboratory testing were Li-ion titanate from Altairnano. Close to 100 cells were tested in the lab to monitor aging patterns, reproduce the aging observed in real life, and accelerate the degradation.

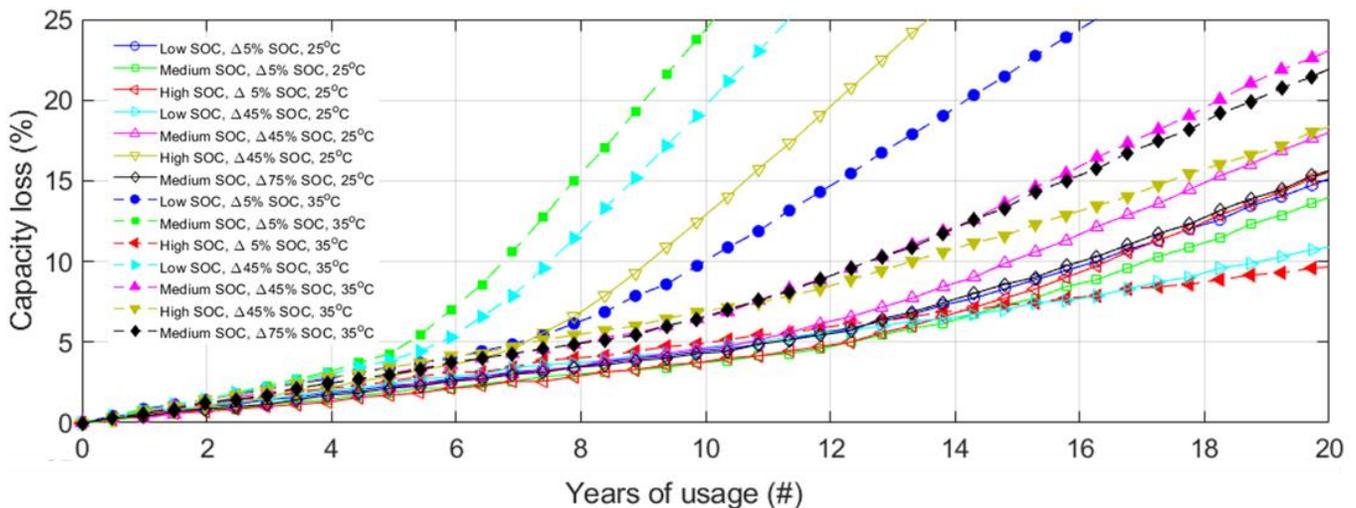
This project showed that, because of the lower voltages, these cells are far less sensitive to degradation induced by calendar aging and high state of charges than traditional Li-ion batteries. Moreover, their capacity fading pace is also slower. Based on our results, we are projecting that accelerated degradation, a typical occurrence in traditional lithium ion batteries, remains of concern under certain conditions, notably if the cells are kept consistently above 35°C (Figure 1). Research conducted for this project is completed in the [PakaLi Battery Laboratory](#).

This is an ongoing project, which has led to 10 publications so far including: "[Battery Energy Storage System battery durability and reliability under electric utility grid operations: Analysis of 3 years of real usage](#)" in the Journal of Power Sources, Vol. 338, pp. 65-73 and "[Battery durability and reliability under electric utility grid operations: Representative usage aging and calendar aging](#)" in the Journal of Energy Storage, Vol. 18, pp. 185-195.

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020





# Hawai'i Natural Energy Institute Research Highlights

## Appendix D: Electrochemical Power Systems

### D7: Path Dependence of Battery Degradation, EV Batteries for Grid Support

**OBJECTIVE AND SIGNIFICANCE:** The objective of this work was to characterize the impact of fast charging and grid-vehicle interactions on the performance and durability of Li-ion batteries in electric vehicles. The knowledge gained in this project inform best practices to help implement successful electric vehicle fast charging, vehicle-to-grid (V2G), and grid-to-vehicle (G2V) programs.

**BACKGROUND:** Electrification of automobiles and fossil-fuel displacement by renewable energy sources are crucial to combat climate change. The successful adoption of these clean energy technologies could benefit from integration strategies such as fast charging and the sourcing/sinking energy to/from the electric grid known as V2G and G2V, respectively.

Understanding and mitigating battery degradation is key to improving the durability of electric vehicles and the reliability of power grids. Battery degradation is path dependent; this means that not only the degradation pace is affected by usage but also the type of degradation the batteries experience. Lithium-ion batteries are known to degrade slowly at first before a rapid acceleration of which starting time will depend on the degradation mechanisms.

**PROJECT STATUS/RESULTS:** Our study showed that a simplistic approach to V2G, namely that an EV is discharged at constant power for 1h without consideration of battery degradation, is not economically viable because of the impact additional V2G cycling has on battery life. However, we showed

that if the batteries are to be used for frequency regulation, there is a much lesser impact.

It must be noted that, because of path dependence, different usages might lead to different results and thus that our results should not be generalized. This was proved further through the fast charging side of this project where batteries were shown to have 4x shorter life even though they were used less aggressively than other similar cells.

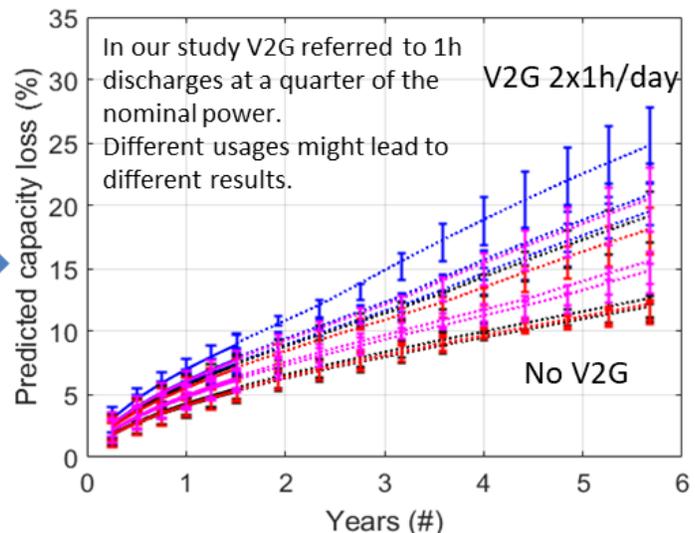
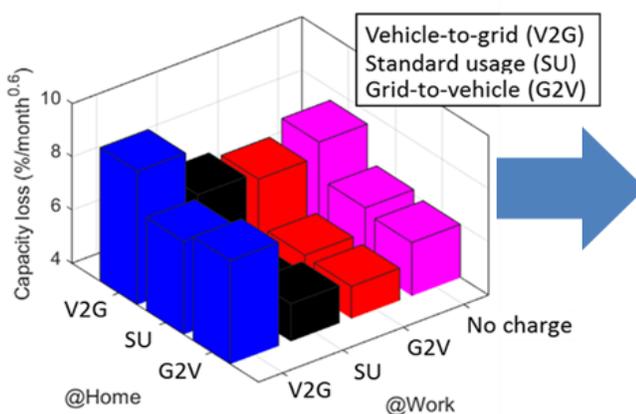
Overall, our work showed that, with good battery prognostic models and further advances in understanding the causes, mechanisms and impacts of battery degradation, a smart control algorithm could take all these aspects in consideration and make V2G and fast charging a reality. Research conducted for this project is completed in the [PakaLi Battery Laboratory](#).

This project is ongoing. This project led to 10 publications so far, including: "[The viability of vehicle-to-grid operations from a battery technology and policy perspective](#)" in Energy Policy, Vol. 113, pp. 342-347 and "[Durability and Reliability of Electric Vehicle Batteries Under Electric Utility Grid Operations: Bidirectional Charging Impact Analysis](#)" in the Journal of Power Sources, Vol. 358, pp. 39-49.

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020





# Hawai'i Natural Energy Institute Research Highlights

## Appendix D: Electrochemical Power Systems

### D8: Battery Diagnosis and Prognosis

**OBJECTIVE AND SIGNIFICANCE:** Development of tools, protocols, and new approaches to improve batteries diagnosis and prognosis via non-invasive in-operando techniques.

**BACKGROUND:** Battery diagnosis and prognosis is a difficult task. Lithium-ion batteries (LiB) are much more complex than traditional batteries and their degradation is path dependent as different usages (current, temperature, SOC range, SOC window..., etc.) will lead to different degradation. Also, large battery packs are comprised of thousands of cells. This precludes the practical use of complex models or a multitude of sensors for each cell.

Traditionally, battery diagnosis is handled via two opposite approaches. The academic route aims for maximum accuracy and achieves it by inputting a lot of resources. The second route -- the one usually used on deployed systems -- is opposite and uses as little resources as possible and must not be destructive. As a result, it is ineffective in predicting the true state of health of the cells.

This assessment of state of the art led HNEI to define and develop a third industry-compatible intermediate route to reach an accurate diagnosis with a cost-effective and non-destructive method, using only sensors already available in battery packs while requiring limiting computing power.

Machine learning and artificial intelligence are starting to play a crucial role to diagnose and prognose batteries. However, their accuracy is limited by the little to no training data available to validate algorithms. To solve this issue, HNEI used its experience to develop the first synthetic training datasets using computer-generated voltage curves. Research conducted for this project is completed in the [PakaLi Battery Laboratory](#).

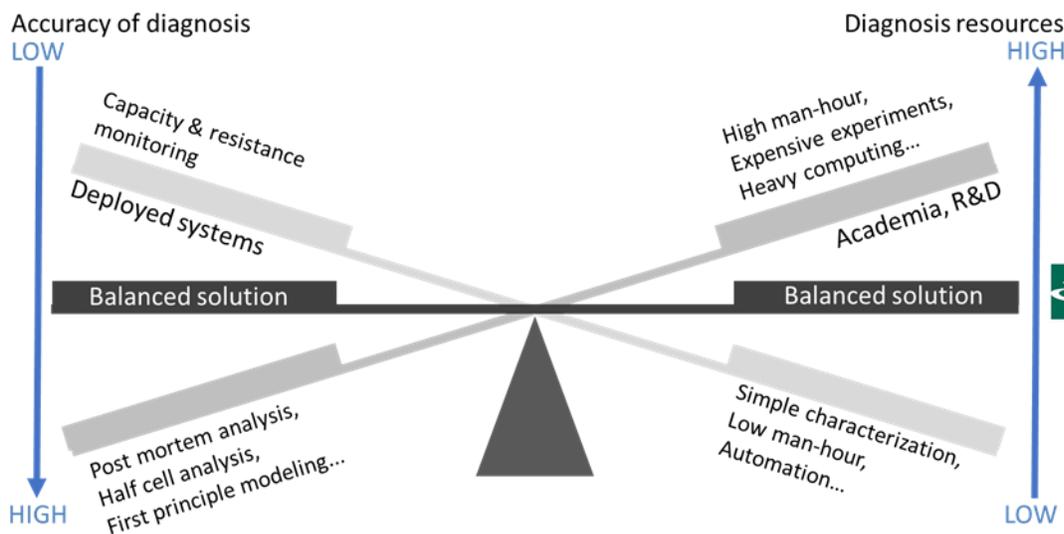
**PROJECT STATUS/RESULTS:** This project is currently ongoing. A full suite of software and models were developed. The main model has been licensed by more than 65 organizations worldwide. This work led to 35 publications and one patent.

*Latest publication:* 2020, M. Dubarry, D. Beck, [Big data training data for artificial intelligence-based Li-ion diagnosis and prognosis](#), Journal of Power Sources, Vol. 479, Paper 228806.

*Funding Source:* Office of Naval Research; SAFT

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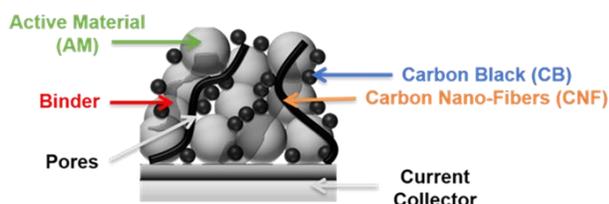
*Last Updated:* October 2020





**OBJECTIVE AND SIGNIFICANCE:** Optimization of battery electrodes to improve performance by tuning architecture.

**BACKGROUND:** Advanced energy conversion devices typically rely on composites electrodes made of several materials interacting with one another. Understanding their individual and combined impact on degradation is essential in the pursuit of the best possible performance and safety. In this project we use Designs of Experiments (DoE) as a statistical tool to optimize formulations and to investigate the importance of process parameters while minimizing resources.



Defining new approaches to minimize experiments and time to reach an optimal battery electrode composition is highly beneficial to the field. To this end, we used the DoE approach and a mixture design was applied for the first time in open literature to electrode formulation. Consequently, the relationship between electrode composition, microstructure and electrochemical performance was uncovered on known and novel materials.

In this project, the DoE approach is applied to two types of electrodes: high power electrodes for lithium batteries (ORN funded, in collaboration with the University of Montreal) and sodium intercalation electrodes (DOI funded, in collaboration with Trevi Systems and the University of Nantes) to investigate the feasibility of desalination batteries. Research conducted for this project is completed in the [PakaLi Battery Laboratory](#).

**PROJECT STATUS/RESULTS:** This is an ongoing project. A high power battery system was optimized in collaboration with the University of Montreal. This work has led to the two following publications listed so far. Current work is focused on the desalination with the screening of different active materials. We are currently running experiments with materials able

to intercalate and release sodium ions in real sea water more than 800 times.

2020, O. Rynne, M. Dubarry, C. Molson, E. Nicolas, D. Lepage, A. Pr  b  , D. Aym  -Perrot, D. Rochefort, M. Doll  , [Exploiting Materials to Their Full Potential, a Li-Ion Battery Electrode Formulation Optimization Study](#), ACS Applied Energy Materials, Vol. 3, Issue 3, pp. 2935-2948.

2019, O. Rynne, M. Dubarry, C. Molson, D. Lepage, A. Pr  b  , D. Aym  -Perrot, D. Rochefort, M. Doll  , [Designs of Experiments for Beginners—A Quick Start Guide for Application to Electrode Formulation](#), Batteries, Vol. 5, Issue 4, Paper 72. (Open Access: [PDF](#))

*Funding Source:* Office of Naval Research; U.S. Department of Interior; Trevi Systems

*Collaboration:* University of Montreal (Canada), University of Nantes (France)

*Contact:* Matthieu Dubarry, [matthieu@hawaii.edu](mailto:matthieu@hawaii.edu)

*Last Updated:* October 2020



**OBJECTIVE AND SIGNIFICANCE:** The objective of this research activity is to develop a high power and energy density durable and safe vanadium flow battery (VFB) with a high concentration of vanadium electrolytes. The proposed research has the potential to double the energy density of vanadium electrolytes, and significantly improve the negative electrode performance. If successful, this work would facilitate the VFB system meeting with the U.S. DOE technical targets for the durable and low-cost electricity's energy storage applications.

**BACKGROUND:** A flow battery is an electrochemical device that comprises a cell stack to reversibly convert the chemical energy of electrolytes to electricity, and external tanks to store the electrolytes containing redox-active species. The sizes of stack and tanks determine the power (kW) and the energy capacity (kWh) independently. The separation of energy storage from the electrochemical conversion unit enables the power and the energy capacity to be independently scaled up for the storages from a few hours to days, depending on the application. For large scale applications, flow batteries also have several key advantages compared to the traditional rechargeable (e.g. Li-ion and lead-acid) batteries, including longer operational lifetimes with deep discharge capabilities, simplified manufacturing, and improved safety characteristics.

To date, VFB is technically the most advanced system of the under-developing flow batteries. Due to it using only one element (vanadium) in both tanks, it overcomes cross-contamination degradation, a significant issue with other flow batteries that use more than one active element. The vanadium ions with oxidation states of 2+/3+ and 4+/5+ are used as active species in the negative and positive electrolytes respectively. The energy density of VFBs depend on the concentration of vanadium: the higher concentration, the higher energy density. The maximum concentration of electrolytes depends on the solubility of  $\text{VO}_2\text{SO}_4$ , a starting electrolyte, and the stability of vanadium species. The solubility of  $\text{V}^{2+}$ ,  $\text{V}^{3+}$  and  $\text{VO}^{2+}(4+)$  decreases with increase of the sulfate concentration due to the common-ion effect; but the stability and solubility of  $\text{VO}^{2+}(5+)$  increase with increase of the acid concentration. Therefore, the concentration of sulfuric acid and vanadium is usually

controlled at 2-4 M and 1-2 M, respectively, which is relatively low for the energy storage application. In addition, VFBs usually require expensive polymer membranes due to the highly acidic and oxidative environment, which lead to high system costs. The low energy densities, along with high capital cost, make it difficult for the current VFBs to meet the performance and economic requirements for broad market penetration. To reduce VFBs' cost, a number of research has been conducted, which aims to improve the vanadium electrolyte energy density and the system performance by increasing vanadium concentration.

Since late 2019, HNEI has conducted VFB research activities to improve the VFB performance and energy density. One of the efforts is diminishing the acid concentration in  $\text{V}^{2+}$ ,  $\text{V}^{3+}$ , and  $\text{VO}^{2+}$  electrolytes to increase the vanadium concentration. A novel electrochemical procedure has been developed to prepare a low acid and high vanadium ( $\text{V}^{3+}$ ) concentration negative electrolytes. The obtained negative electrolyte contains a maximum 5 M vanadium with  $\sim 0.1$  M  $\text{H}^+$ , and the positive electrolyte maximizes to  $\sim 3$  M vanadium. These increased vanadium concentrations in negative and positive electrolytes imply a potential double improvement of the energy density of vanadium electrolytes. The prepared electrolytes were used to validate the charge-discharge feasibility in a single cell with an anion exchange membrane (AEM) in the VFB instead of the conventional proton exchange membrane. The key features of a VFB cell with AEM are illustrated in Figure 1.

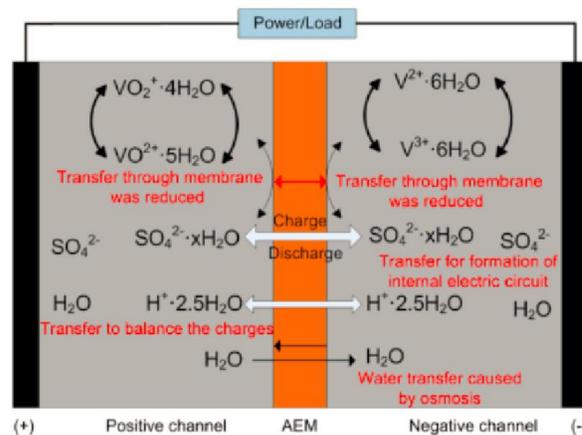


Figure 1. The features of a VFB cell with AEMs.

During the charge-discharge processes, vanadium redox reactions take place in negative and positive electrolyte, and the bisulfate ions transport through AEM to form the internal electric circuit. Simultaneously, the sulfuric acid concentration variation also maintains the stability of the positive electrolyte. As shown in Figure 2, a single cell with 3 M vanadium electrolytes in both sides successfully demonstrates a good charge-discharge performance. Both positive and negative electrodes show low overpotentials. However, the low ionic conductivity of the AEM and the negative electrolytes, as well the high proton permeability of the AEM result in large ohmic losses and a low energy efficiency. Furthermore, due to the poor AEM chemical and mechanical properties, the electrolytes leakage caused the operation failure during the second discharging.

ionic conductivity of the AEMs and the negative electrolytes.

*Funding Source:* Office of Naval Research

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*Last updated:* October 2020

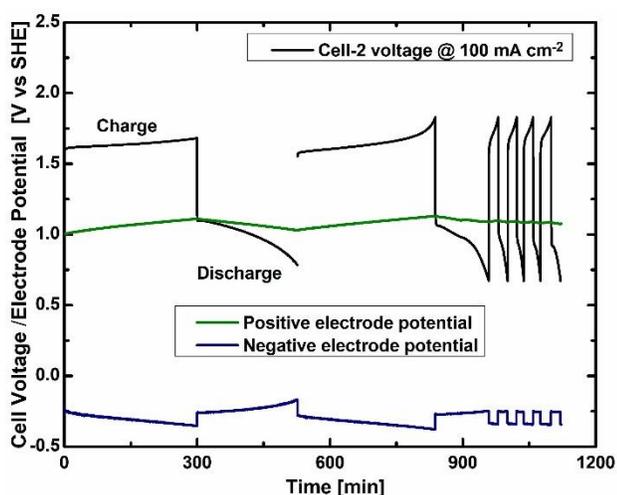


Figure 2. Charge-discharge cycles of VFB with an AEM and 3 M electrolytes in both side.

**PROJECT STATUS/RESULTS:** An electrochemical procedure has been developed to prepare a low acid ( $H^+$  low to 0.1 M) and high vanadium concentration (V up to 5 M) negative electrolytes. The acid concentration decreases by a factor of more than 30 and the vanadium concentration doubled compared to the state of the art. Single cells operated with the high concentration vanadium electrolytes were evaluated with different AEMs and demonstrated good performance and low overpotentials for both positive and negative electrodes. Challenges were identified as the low chemical and mechanical stability and the high proton permeability of the AEMs, and the low



**OBJECTIVE AND SIGNIFICANCE:** The objective of this research is to develop high-throughput ink-based fabrication techniques for light-weight thin film photovoltaics (PV). This approach has the potential to significantly reduce manufacturing costs and enable PV integration on non-conventional substrates, such as polyamides or woven fabrics.

**BACKGROUND:** Crystalline silicon has been leading the PV market for over 20 years. These panels, found on roof-tops and in centralized production plants, are easily recognizable by their architecture, with interconnected wafer-like solar cells laminated under a flat sheet of glass. Although well-suited for stationary electrical production, the mechanical rigidity and weight of silicon PV modules become a burden for mobile applications, where portability is far more critical than raw performance. To this regard, R&D efforts have been recently focused on methods to integrate ultra-light and flexible thin film solar materials onto lightweight/flexible substrates, including plastics (polyamides) and fabrics. Such devices can generate enough electricity to power small electronic devices (phones and electronic tablets for civilians) and sensors (healthcare diagnosis instruments for military personnel), providing a reliable source of energy for a variety of military and commercial applications.

**PROJECT STATUS/RESULTS:** With support from the Office of Naval Research, the research team at the HNEI/Thin Films Laboratory is developing a unique method to print thin film-based PV. Rather than relying on conventional vacuum-based deposition tools, which are costly to operate and maintain, this technique uses liquid molecular inks which already

contain all the chemical elements necessary for the synthesis of the solar absorber. These inks can be easily printed and cured to form thin film solar absorbers. Our project is currently focused on an Earth-abundant multi-compound alloy ( $\text{Cu}_2\text{ZnSnSe}_4$ , CZTSe), a material which meets the mechanical and weight requirements for light weight flexible PV. Results of this work show that high-quality CZTSe solar absorbers can be achieved with this printing technology. Solar cells with power conversion efficiency over 7% have been fabricated. However, CZTSe has the potential to achieve much higher efficiency, up to 20%.

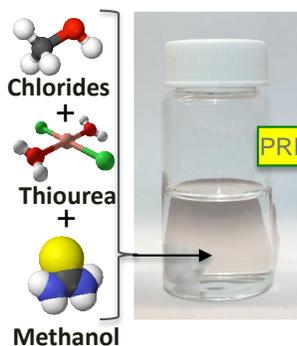
Current work focuses in development of innovative techniques to passivate defects in CZTSe solar absorbers and improve their conversion efficiency (primarily increase cells output voltage). This technique is also being evaluated to synthesize other solar absorbers with promising properties for PV applications, including  $\text{Cu}(\text{In,Ga})\text{Se}_2$  and  $\text{Cu}(\text{In,Al,B})\text{Se}_2$ .

*Funding Source:* Office of Naval Research

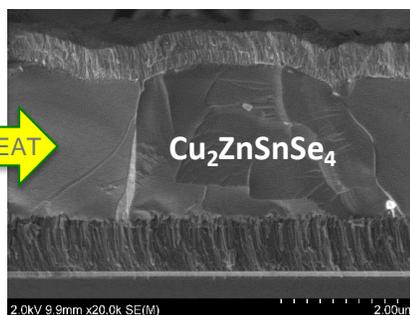
*Contact:* Nicolas Gaillard, [ngaillard@hawaii.edu](mailto:ngaillard@hawaii.edu)

*Last Updated:* October 2020

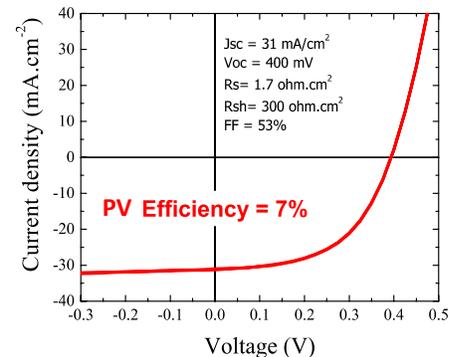
**Molecular ink**  
(stable over 12 months)



**Cross-section of a printed CZTSe solar absorber**



**Current vs. voltage of a printed CZTSe solar cell**





**OBJECTIVE AND SIGNIFICANCE:** The objective of this project is the design, synthesis, and characterization of novel, reversible high-performance acidic gas ( $\text{SO}_x$ ,  $\text{NO}_x$ , and  $\text{H}_2\text{S}$ ) contaminant absorbent materials. The materials under development will enable fuel cell vehicles to be efficiently operated under harsh atmospheric air environments. If successful, sorbents under development will assist the fuel cell filter industry, and reduce environmental contamination from hazardous absorbent waste.

**BACKGROUND:** Current state-of-the-art gas purification technologies for acidic gas capture based on metal oxides and hydroxides do not meet all of the performance requirements of today's gas purification in terms of sorption: kinetics, capacities, selectivity, and reversibility. This leads to large volumes of polluted absorbent waste. This situation can be expected to worsen in the future with the increased use of fuel cell vehicles that require abundant efficiently purified air as an oxygen source.

The sorbent classes under development include ionic liquids, metallo ionic liquids, and MOF-activated carbons. The sorbent material properties are optimized through a combination of careful selection of reactants and modification of the sorbent cation and anion groups. For instance, metallo ionic liquids with a high content of the small, highly charged acetate and croconate groups, and transition metal ions with expandable coordinative environments are being designed, synthesized, and characterized.

Nano confinement of the absorbents in highly porous materials is being performed in order to increase acidic gas-sorbent interactions and hence gas sorption performance. Nano confinement is especially critical for ionic liquids absorbents since they have high viscosity, which limits gas diffusion distances into the bulk of the material. We have physically deposited thin films of 1-ethyl-3-methyl imidazolium acetate ionic liquid onto activated carbon that remain intact during exposure to  $\text{SO}_2$  and/or  $\text{NO}_2$  contaminated air streams. The sorbents being developed also have relevance in other applications requiring acidic gas ( $\text{SO}_x$ ,  $\text{NO}_x$ , and  $\text{H}_2\text{S}$ ) contaminant mitigation, including flue gas cleaning and natural gas purification.

**PROJECT STATUS/RESULTS:** Our work has shown that nano confined acetate based ionic liquids have high potential for  $\text{SO}_2$  capture, with higher breakthrough capacities and times observed with the 1-ethyl-3-methylimidazolium acetate, compared to pure activated carbon and activated carbon supported potassium hydroxide sorbents (Figure 1, below).

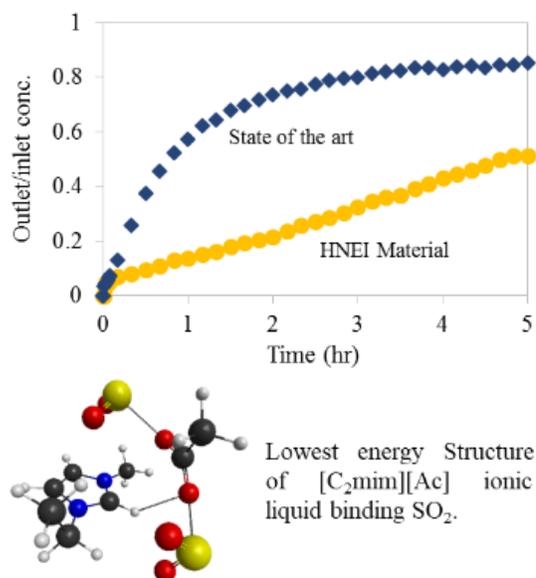


Figure 1.

Furthermore, we have recently prepared novel acetate based metallo ionic liquids and ionic salts containing Mn and Fe with potential for acid gas capture at comparatively low cost compared to the pure ionic liquids. We have obtained the crystal structures of the anhydrous and hydrated  $\text{M}_4(\text{OAc})_{10}[\text{C}_2\text{mim}]_2$  ( $\text{M}=\text{Mn}$  or  $\text{Fe}$ ). Preliminary gas sorption analyses on the  $\text{Fe}_4(\text{OAc})_{10}[\text{C}_2\text{mim}]_2$  sorbent indicate plausibility for reversible acid gas capture (Figure 2).

The following peer reviewed publications have resulted from this project:

- 2020, P. Dera, E. Bruffey III, G.J. Finkelstein, C. Kelly, A. Gigante, H. Hagemann, G. Severa, [Synthesis, Characterization, and Crystal Structures of Two New Manganese Aceto EMIM Ionic Compounds with Chains of  \$\text{Mn}^{2+}\$  Ions Coordinated Exclusively by Acetate](#), ACS Omega, Vol. 5, Issue 25, pp. 15592-15600. (Open Access: [PDF](#))

- 2018, G. Severa, J. Head, K. Bethune, S. Higgins, A. Fujise, [Comparative studies of low concentration SO<sub>2</sub> and NO<sub>2</sub> sorption by activated carbon supported \[C<sub>2</sub>mim\]\[Ac\] and KOH sorbents](#), Journal of Environmental Chemical Engineering, Vol. 6, Issue 1, pp. 718-727.
- 2015, G. Severa, K. Bethune, R. Rocheleau, S. Higgins, [SO<sub>2</sub> sorption by activated carbon supported ionic liquids under simulated atmospheric conditions](#), Chemical Engineering Journal, Vol. 265, pp. 249-258.

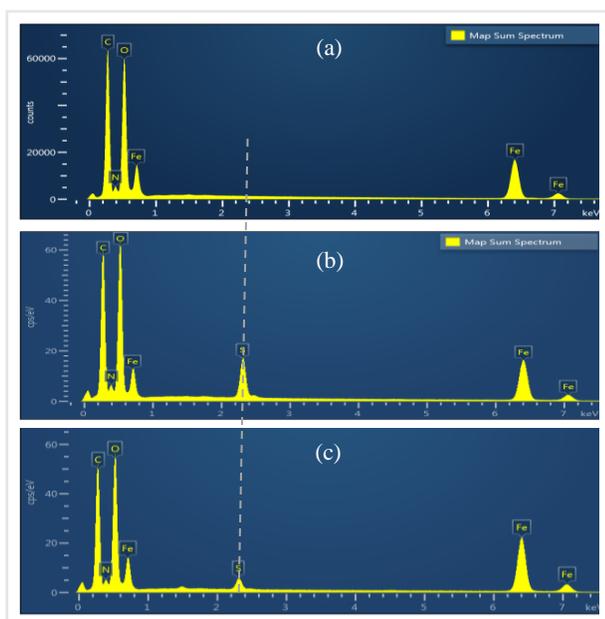


Figure 2. EDS analyses of Fe<sub>4</sub>(OAc)<sub>10</sub>[C<sub>2</sub>mim]<sub>2</sub> material (a) as synthesized (b) after SO<sub>2</sub> absorption, showing intense presents of sulfur peaks (c) after SO<sub>2</sub> desorption at 90 °C, showing minute presence of sulfur species.

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020



**OBJECTIVE AND SIGNIFICANCE:** This project's objective is the development of air filtration materials that are capable of regeneration through UV light exposure. These materials would have application to purify air for stationary and vehicle fuel cell power plants. Since these materials only require UV light for regeneration, ambient sunlight could serve to regenerate the materials, reducing energy or toxic material demand and use in Hawai'i.

**BACKGROUND:** A novel method for regenerating air filtration material through photocatalysis is reported herein. In this study, titanium dioxide ( $\text{TiO}_2$ ) and graphene oxide is covalently bonded to the surface of granular activated carbon to form a uniform nano-scale coating using nitric acid pretreatment and a hydrothermal reaction. Coupling with graphene oxide has also been shown to activate  $\text{TiO}_2$  under longer wavelengths of visible light. Graphene oxide was utilized in this study to enhance the efficiency of  $\text{TiO}_2$  and the allow the free radicals produced under UV radiation to scavenge surface bonded air contaminants,  $\text{SO}_2$  molecules in this case. A custom air filtration test bed was used to expose air contaminated with  $\text{SO}_2$  to the novel air filtration materials. The test bed allowed the characterization of the adsorption capacity of the novel air filtration materials. After adsorption capacity was determined, the material was submerged in an aqueous solution and exposed to UV radiation. During that time, the UV light is theorized to produce free radicals from interaction with the  $\text{TiO}_2$ , those free radicals are then absorbed by the electron sink of the graphene oxide, at which point the free radicals scavenge and attack the nearest  $\text{SO}_2$  surface bond, thus releasing  $\text{SO}_2$  from the surface and regenerating the surface so that the material can be reused as an air filtration material.

**PROJECT STATUS/RESULTS:** Hydrothermal synthesis of  $\text{TiO}_2$ /graphene oxide coated activated carbon was shown effective in producing a nanoscale, uniform coating of  $\text{TiO}_2$  onto the surface of oxidized activated carbon. Nitric acid ( $\text{HNO}_3$ ) pretreatment was necessary to ensuring complete surface coverage by increasing the surface carboxyl groups on activated carbon. Presence of  $\text{TiO}_2$  decreased the adsorption capacity of pure activated carbon from 0.139 to 0.075 g  $\text{SO}_2$ /g  $\text{TiO}_2$ /graphene oxide coated activated carbon, corresponding to a 46% drop. Photocatalytic oxidation and water regeneration

contributed to the overall regeneration of  $\text{TiO}_2$ /graphene oxide coated activated carbon. Water regeneration provided a significant effect where a 67% regeneration efficiency was able to be obtained without any UV exposure. When exposed to UV light, an even higher regeneration efficiency of 87% was achieved and the respective photocatalytic mechanisms were speculated. The results from this study (Figure 1) demonstrate the technical feasibility of photocatalytic enhanced regeneration.

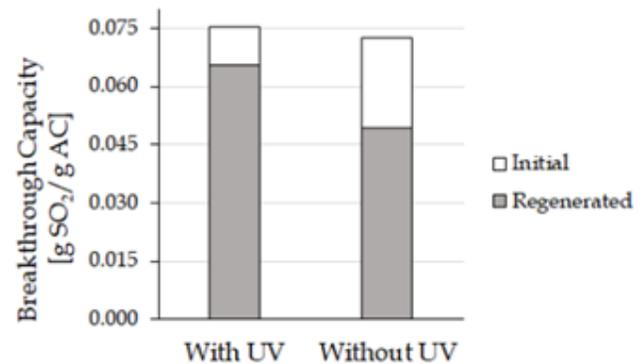


Figure 1. Initial and regenerated breakthrough capacity of TGAC with and without UV exposure.

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020



**OBJECTIVE AND SIGNIFICANCE:** The purpose of this project was to develop a biorefinery technology to produce biochar-like solid fuel and bioplastics from cellulosic biomass. The bioplastics have a much higher monetary value than solid fuel and hence reduce the cost of solid fuel for power generation. The carbon-neutral solid fuel can supplement the intermittent solar and wind powers.

**BACKGROUND:** Cellulosic biomass from agriculture and forest management is an under-utilized renewable resource. The major components of raw biomass are cellulose (30-50% wt), hemicellulose (15-25% wt) and lignin (20-35% wt). Compared to lignite coal (~\$20/ton), raw biomass is expensive (~\$60/ton) and has a relatively low heating value (HHV 17-19 MJ/kg) because of the high atomic O/C ratio of cellulose and hemicellulose. However, cellulose and hemicellulose could be a potential feedstock for high value products such as bioplastics.

**PROJECT STATUS/RESULTS:** The research investigated chemical and biological conversions of woody biomass. Under thermal catalytic hydrolysis conditions, sawdust was converted into hydrochar, a biochar like solid as shown in Figure 1. The cellulose and hemicellulose in raw biomass were completely converted into organic acids, primarily levulinic and formic acids. Accounting for ~45% wt of raw biomass, the hydrochar has a heating value of lignite coal (HHV 25 MJ/kg), which is higher than the heating values of raw or torrefied biomass. Since the cellulose, hemicellulose, organic extractives, and minerals have been removed, the hydrochar has a lower atomic O/C ratio and is cleaner than raw biomass. The lignite-grade hydrochar performs better

than raw biomass for power generation. In addition to the major organic acids, the hydrolysates solution contained minor byproducts including furfurals and phenolic compounds that were inhibitive to microbes. The research measured the microbial yields on individual hydrolysates and determined the inhibitive concentration levels for detoxification operation and fermentation control. After proprietary treatment, the biomass hydrolysates could be utilized by microbes to form polyhydroxyalkanoate (PHA). The PHA bioplastics exhibit the material properties of conventional plastics such as polypropylene and can be completely degraded into water and carbon dioxide by microorganisms in the environment, including marine waters.

According to the experimental results, 100 lbs of raw woody biomass (dry base) can be converted into ~45 lbs of hydrochar (~\$0.03/lb) and ~10 lbs of bioplastics (~\$2/lb). The technology can increase the value of raw biomass by more than four folds. As a result, the hydrochar could be used as a carbon neutral solid fuel for power generation at a competitive price of lignite-grade coal.

The project has generated four technical reports, four research articles in peer-reviewed scientific journals, and two presentations in national and international conferences.

*Funding Source:* Bio-on S. p.A.

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*Last Updated:* October 2020



Figure 1. Conversion of wood sawdust into hydrochar and bioplastics.

## **ADDITIONAL PROJECT RELATED LINKS**

### **BOOK CHAPTERS:**

1. 2013, J. Yu, [Production of Polyhydroxyalkanoates in Biomass Refining](#), in S-T. Yang, H. El-Ensashy, N. Thongchul (eds.) *Bioprocessing Technologies in Biorefinery for Sustainable Production of Fuels, Chemicals, and Polymers*, John Wiley & Sons, Inc., Chapter 22, pp. 415-426.
2. 2010, J. Yu, [Biosynthesis of Polyhydroxyalkanoates from 4-Ketovaleric Acid in Bacterial Cells](#), in H.N. Cheng, R.A. Gross (eds.) *Green Polymer Chemistry: Biocatalysis and Biomaterials*, American Chemical Society, Chapter 12, pp. 161-173.
3. 2009, J. Yu, [Production of green bioplastics from agri-food chain residues and co-products](#), in K. Waldron (ed.), *Handbook of Waste Management and Co-Product Recovery in Food Processing*, Vol. 2, Woodhead Publishing Limited, Chapter 21, pp. 515-536.
4. 2006, J. Yu, [Microbial Production of Bioplastics from Renewable Resources](#), in S-T. Yang (ed.), *Bioprocessing for Value-Added Products from Renewable Resources*, Elsevier, Chapter 23, pp 585-610.

### **PAPERS AND PROCEEDINGS:**

1. 2020, P-C. Kuo, J. Yu, [Process simulation and techno-economic analysis for production of industrial sugars from lignocellulosic biomass](#), Industrial Crops and Products, Vol. 155, Paper 112783.
2. 2016, S. Kang, J. Yu, [An intensified reaction technology for high levulinic acid concentration from lignocellulosic biomass](#), Biomass and Bioenergy, Vol. 95, pp. 214-220.
3. 2015, S. Kang, J. Yu, [Effect of Methanol on Formation of Levulinates from Cellulosic Biomass](#), Industrial & Engineering Chemistry Research, Vol. 54, Issue 46, pp. 11552-11559.
4. 2014, N. Tanadchangsang, J. Yu, [Thermal stability and degradation of biological terpolyesters over a broad temperature range](#), Journal of Applied Polymer Science, Vol. 132, Issue 13, pp. 41715-41815.
5. 2014, P. Tang, J. Yu, [Kinetic analysis on deactivation of a solid Brønsted acid catalyst in conversion of sucrose to levulinic acid](#), Indus. & Engin. Chemistry Research, Vol. 53, Issue 29, pp. 11629-11637.
6. 2013, N. Tanadchangsang, J. Yu, [Miscibility of natural polyhydroxyalkanoate blend with controllable material properties](#), Journal of Applied Polymer Science, Vol. 129, Issue 4, pp. 2004-2016.
7. 2011, M. Jaremko, J. Yu, [The initial metabolic conversion of levulinic acid in Cupriavidus necator](#), Journal of Biotechnology, Vol. 155, Issue 3, pp. 293-298.
8. 2008, J. Yu, L.X.L. Chen, [The Greenhouse Gas Emissions and Fossil Energy Requirement of Bioplastics from Cradle to Gate of a Biomass Refinery](#), Environmental Science & Technology, Vol. 42, Issue 18, pp. 6961-6966.
9. 2008, J. Yu, H. Stahl, [Microbial utilization and biopolyester synthesis of bagasse hydrolysates](#), Bioresource Technology, Vol. 99, Issue 17, pp. 8042-8048.

### **PRESENTATIONS:**

1. 2020, J. Yu, [Ductile Bioplastics and Lignite-grade Fuel from Cellulosic Biomass](#), Presented at the European Biomass Conference & Exhibition, Marseille, France, April 27-30.
2. 2016, J. Yu, [A Two-stage Process to Produce Ductile Bioplastics from Cellulosic Biomass](#), Presented at the World Congress on Industrial Biotechnology, San Diego, California, April 17-20.

### **STUDENT THESES:**

1. 2011, M.J. Jaremko, [Polyhydroxyalkanoate synthesis by ralstonia eutropha from multiple substrates](#), Master of Science Thesis, Department of Molecular Bioscience and Bioengineering, University of Hawai'i at Mānoa, Honolulu, HI.

### **LABORATORY: [BIOPROCESSING LAB](#)**



**OBJECTIVE AND SIGNIFICANCE:** The objective of this project is to develop a commercially viable, two-way liquid hydrogen carrier (LOHCs) based on solutions of magnesium borohydride in heterocyclic LOHCs, that has a greater energy efficiency and lower delivery costs than existing hydrogen carriers and conventional compressed H<sub>2</sub> gas transport technology. The successful development of the liquid hydrogen carriers would support acceptance and expansion of hydrogen and fuelcell technologies.

**BACKGROUND:** A substantial network of tanker trucks and pipelines to transport hydrogen at ambient temperature and pressure already exists. The LOHC's of interest in this work would be able to utilize this infrastructure. Both one-way carriers which form benign products upon elimination of hydrogen that are released to the environment, and two-way LOHCs which can be cycled between their hydrogenated and dehydrogenated phases have been investigated. A recent comparative cost and energy consumption analysis of LOHCs performed at Argonne National Laboratory (ANL) showed the one-way carrier, methanol to be the strongest candidate. However, it showed no overall cost advantage over tube trailer delivery of compressed hydrogen and pointed to the need to develop new hydrogen carriers. Methylcyclohexane, the prototypical two-way LOHC has enthalpy of dehydrogenation of 69 kJ/mol H<sub>2</sub>, which is a major drawback to its utilization in practical systems as its dehydrogenation is intrinsically energy extensive. It also has a relatively low volumetric available hydrogen density of 47 g/L which translates to a high cost of hydrogen transport.

Heterocyclic LOHCs have excellent thermodynamic properties but are challenged by low volumetric available hydrogen densities which impose an economic barrier to their application as practical hydrogen carriers. Our approach to overcoming this barrier is the addition of the high density hydrogen storage material, Mg(BH<sub>4</sub>)<sub>2</sub> to the heterocyclic LOHC which results in an up to 19% increase of the available volumetric hydrogen density. The enhanced density, up to 100 g/L, is more than double that of methylcyclohexane.

This work is targeting the generation of two-way LOHCs by charging selected heterocyclic LOHCs

with Mg(BH<sub>4</sub>)<sub>2</sub> (Figure 1), and to identify the best heterocycle/Mg(BH<sub>4</sub>)<sub>2</sub>/catalyst combination in terms of rate, cycling capacity, and product selectivity with goal of maximizing energy efficiency of hydrogen storage and delivery.

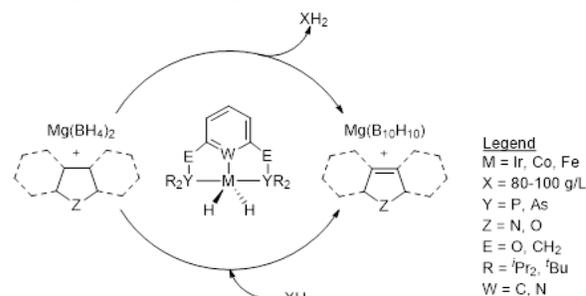


Figure 1. Hydrogen cycling of solutions of magnesium borohydride in heterocyclic LOHCs.

This project is a collaborative effort between UH (HNEI and the Department of Chemistry) and the DOE-HyMARC Consortium including Pacific Northwest Laboratory (PNNL) and National Renewable Energy Laboratory (NREL).

**PROJECT STATUS/RESULTS:** The HNEI research effort, which began in May 2020, has been focused on syntheses and characterization of ionic liquid and molten salts LOHCs with potential for high solubility of Mg(BH<sub>4</sub>)<sub>2</sub> and characterization of their hydrogen carrier properties. Collaborators at the Department of Chemistry are focused on dissolution and testing of pyridine solutions of Mg(BH<sub>4</sub>)<sub>2</sub> and catalysts syntheses. The immediate goal of the project is to validate the basic concept of producing an advanced liquid hydrogen carrier by dissolving Mg(BH<sub>4</sub>)<sub>2</sub> in LOHCs.

Towards this effort, a variety of ionic liquid borohydride LOHCs materials have been synthesized including: (A) 1-ethyl-3-methyl imidazolium borohydride, C<sub>2</sub>mimBH<sub>4</sub>; (B) 1-butyl-3-methyl imidazolium borohydride, C<sub>4</sub>mimBH<sub>4</sub>; (C) 1-hexyl-3-methyl imidazolium borohydride, C<sub>6</sub>mimBH<sub>4</sub>; and (D) cholinium borohydride, CholiniumBH<sub>4</sub>. These materials have been characterized utilizing nuclear magnetic resonance spectroscopy (NMR), infrared vibrational spectroscopy (FTIR), and thermogravimetric analyses (TGA-DSC) (Figure 2a). The vibrational spectroscopy confirmed the typical borohydride peaks in the 2200-2500 cm<sup>-1</sup> and 1100-1400 cm<sup>-1</sup> region whilst <sup>11</sup>B solution NMR

spectroscopy directly confirmed the  $\text{BH}_4^-$  ion peaks, at -36 to 39 ppm region, with no residual starting materials. The observed partial thermal stability of the synthesized borohydride LOHCs in the 80-200 °C range suggest their compatibility with the dehydrogenation of  $\text{Mg}(\text{BH}_4)_2$  to  $\text{Mg}(\text{B}_{10}\text{H}_{10})$ , which desorb hydrogen in similar temperature range. Besides the syntheses of the imidazole and choline based borohydride LOHCs, we have also begun attempts to synthesize higher hydrogen gravimetric density carbazole and pyridine-based borohydride LOHCs.

Recently, a high-pressure differential scanning calorimetry (HP-DSC) equipment (Figure 2d) purchased through U.S. DOE funding has been set up that will be used to determine the thermodynamic parameters associated with the (de)hydrogenation of the LOHC and  $\text{Mg}(\text{BH}_4)_2$ . Calorimetry measurements will assist in determining the extent to which the dehydrogenation thermodynamics of  $\text{Mg}(\text{BH}_4)_2$  are altered upon dissolution in the LOHCs as well as to

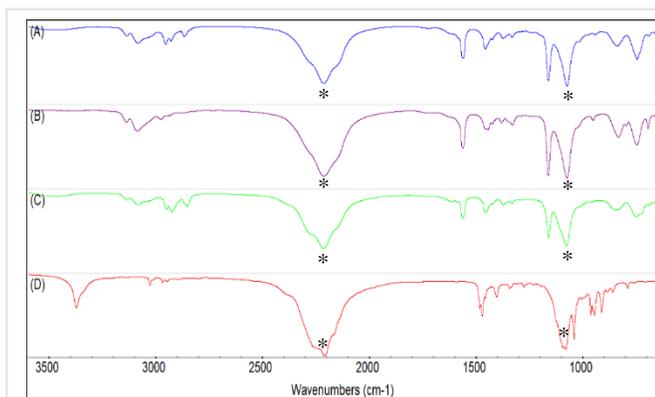
elucidate the presence of thermal events associated with intermediary species during the dehydrogenation process. The calorimetry studies will also determine the energetics associated with product formation, and thus reveal if thermodynamic rather than kinetic limitations are responsible for any incomplete dehydrogenation reactions.

Future work is intended to continue to synthesize and characterize LOHCs. We will benchmark the kinetics and hydrogen release, and screen the dehydrogenation behavior of LOHC- $\text{Mg}(\text{BH}_4)_2$  solutions and perform thermodynamic studies of the (de)hydrogenation of the LOHC- $\text{Mg}(\text{BH}_4)_2$  solutions, as well as,  $^{11}\text{B}$  NMR spectroscopy, IR/Raman spectroscopy and thermal methods (TGA-DSC) on products of reactions.

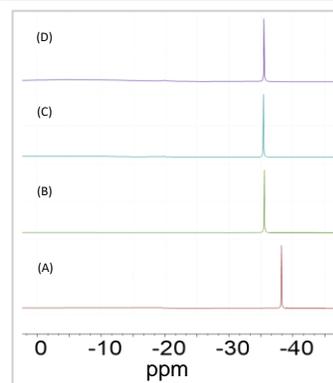
*Funding Source:* U.S. Department of Energy, EERE; Energy Systems Development Special Fund

*Contact:* Godwin Severa, [severa@hawaii.edu](mailto:severa@hawaii.edu)

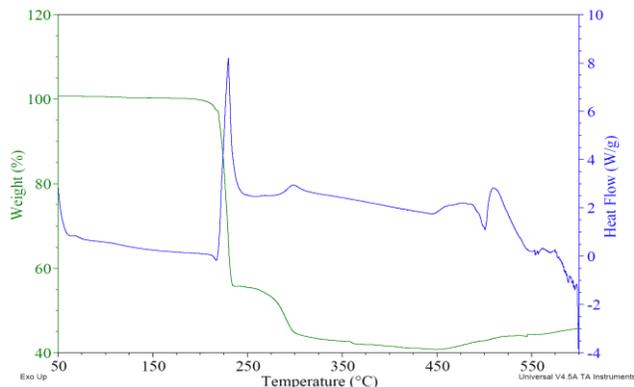
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(a) FT-ATR of synthesized borohydride LOHCs showing B-H peaks (\*).



(b)  $^{11}\text{B}$  Solution NMR of the synthesized borohydride.



(c) Typical TGA-DSC of the synthesized borohydrides (D).



(d) HP-DSC set up for in-situ thermodynamic studies.

Figure 2. Characterizations of (A)  $\text{C}_2\text{mimBH}_4$ , (B)  $\text{C}_4\text{mimBH}_4$  (C)  $\text{C}_4\text{mimBH}_4$  and (D) cholinium $\text{BH}_4$ .



**OBJECTIVE AND SIGNIFICANCE:** The objective of this project is to synthesize and characterize novel modified magnesium boride,  $MgB_2$ , materials with improved hydrogen cycling kinetics and hydrogen storage capacities and demonstrate their capability to meet the U.S. Department of Energy (DOE) hydrogen storage targets. If successful, the solid-state modified  $MgB_2$  materials would be safer and cheaper than the high pressure compressed  $H_2$  (700 bar) or liquid  $H_2$  alternative onboard vehicle hydrogen storage systems on the market.

**BACKGROUND:** Magnesium borohydride,  $Mg(BH_4)_2$ , is one of the few materials that has a demonstrated gravimetric hydrogen storage capacity greater than 11 wt% and thus a demonstrated potential to be utilized in a hydrogen storage system meeting U.S. DOE hydrogen storage targets. However, due to extremely very slow kinetics, cycling between  $Mg(BH_4)_2$  and  $MgB_2$ , has been accomplished only at high temperature ( $\sim 400^\circ C$ ) and under high charging pressure ( $\sim 900$  bar). More recently, tetrahydrofuran (THF) complexed to  $Mg(BH_4)_2$  has been shown to vastly improve the kinetics of dehydrogenation, enabling the rapid release of  $H_2$  at  $< 200^\circ C$  to give  $Mg(B_{10}H_{10})$  with high selectivity. However, these types of materials have much lower hydrogen cycling capacities. This project is focused on development of modified  $MgB_2$  by either extending the dehydrogenation of magnesium borane etherates to  $MgB_2$  or by direct syntheses of the modified  $MgB_2$  in presence of additives. The immediate goal of the third-year project period is to show hydrogenation at temperatures and pressures below 300 bar and  $250^\circ C$ . This will be a significant improvement over the pre-project state of art (900 bar and  $400^\circ C$ ), as well as our previous year project achievement of 400 bar and  $300^\circ C$ .

This HNEI-led project is a collaborative effort between UH (HNEI and the Department of Chemistry) and the DOE-HyMARC Consortium including Sandia National Laboratory, Lawrence Livermore National Laboratory, and National Renewable Energy Laboratory.

**PROJECT STATUS/RESULTS:** This research effort is focused on the direct syntheses and analyses of modified  $MgB_2^*$  formed from pure  $MgB_2$  or its precursors (Figure 1), while the Department of

Chemistry's effort is focused on forming modified  $MgB_2$  through the dehydrogenation of magnesium boranes and magnesium borohydride. The project is guided by computational calculations from Lawrence Livermore National Laboratory (Figure 2). The molecular dynamic simulations suggest that the selected additives can modify the  $MgB_2$  structure rendering it susceptible to hydrogenation at moderate conditions compared to pure  $MgB_2$ .

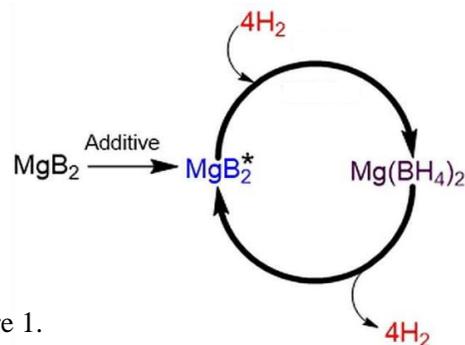


Figure 1.

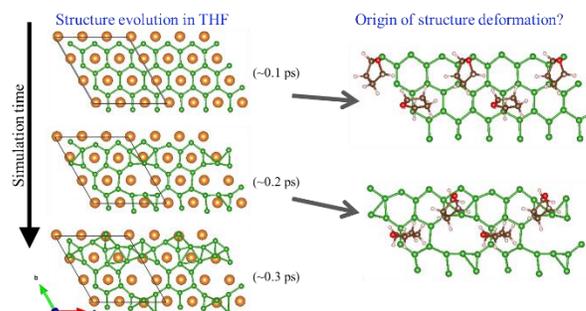


Figure 2. Molecular Dynamic Simulations showing  $MgB_2$  basal plane structure evolution in presence of THF additive. THF induces defect formation on B sheets which may facilitate borohydride formation during hydrogenation.

To date, significant progress has been made towards improving the hydrogen storage properties of  $MgB_2/Mg(BH_4)_2$  system (Figure 3). The bulk  $MgB_2$  hydrogenation pressure has been reduced from 900 bar to 400 bar and temperatures from  $400^\circ C$  to  $300^\circ C$ , while maintaining the  $MgB_2$  to  $Mg(BH_4)_2$  conversion of greater than 75%. Recent results indicate that  $MgB_2$ , modified with a unique combination of additives can be hydrogenated to  $Mg(BH_4)_2$  at the moderate conditions of 160 bar and  $250^\circ C$ . However, the hydrogenation is still limited to the surface of the material with minimum hydrogen uptake into the bulk of the material.

Hence, our current research effort is towards improving the hydrogen uptake into the bulk of the material, at these desirable lower pressure and lower temperature conditions. A variety of characterizations being performed on the hydrogenated  $\text{MgB}_2$  materials to determine their hydrogen storage properties are shown in Figure 4. We have utilized temperature

programmed desorption coupled to mass spectroscopy (TPD) and thermogravimetric analyses (TGA) to confirm the hydrogen gravimetric density and purity of the hydrogen released from the modified materials. Nuclear magnetic resonance (NMR) and infrared spectroscopy (FTIR) are being utilized to directly confirm the formation of  $\text{Mg}(\text{BH}_4)_2$  from

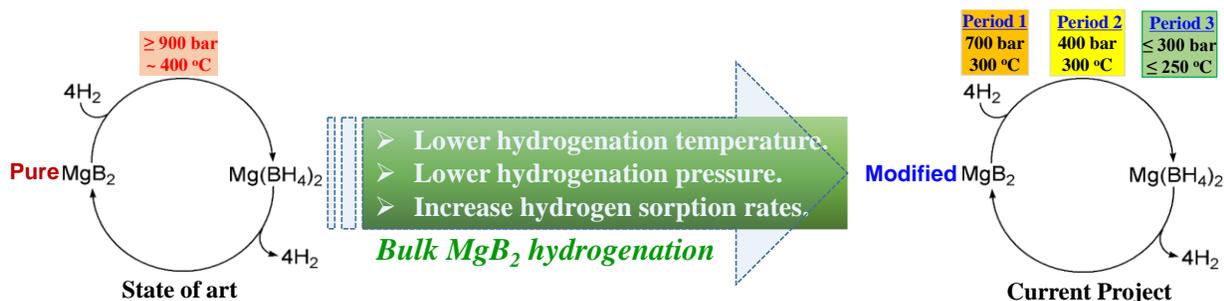


Figure 3. Progression of project efforts towards improving hydrogen storage properties of  $\text{MgB}_2/\text{Mg}(\text{BH}_4)_2$  system.

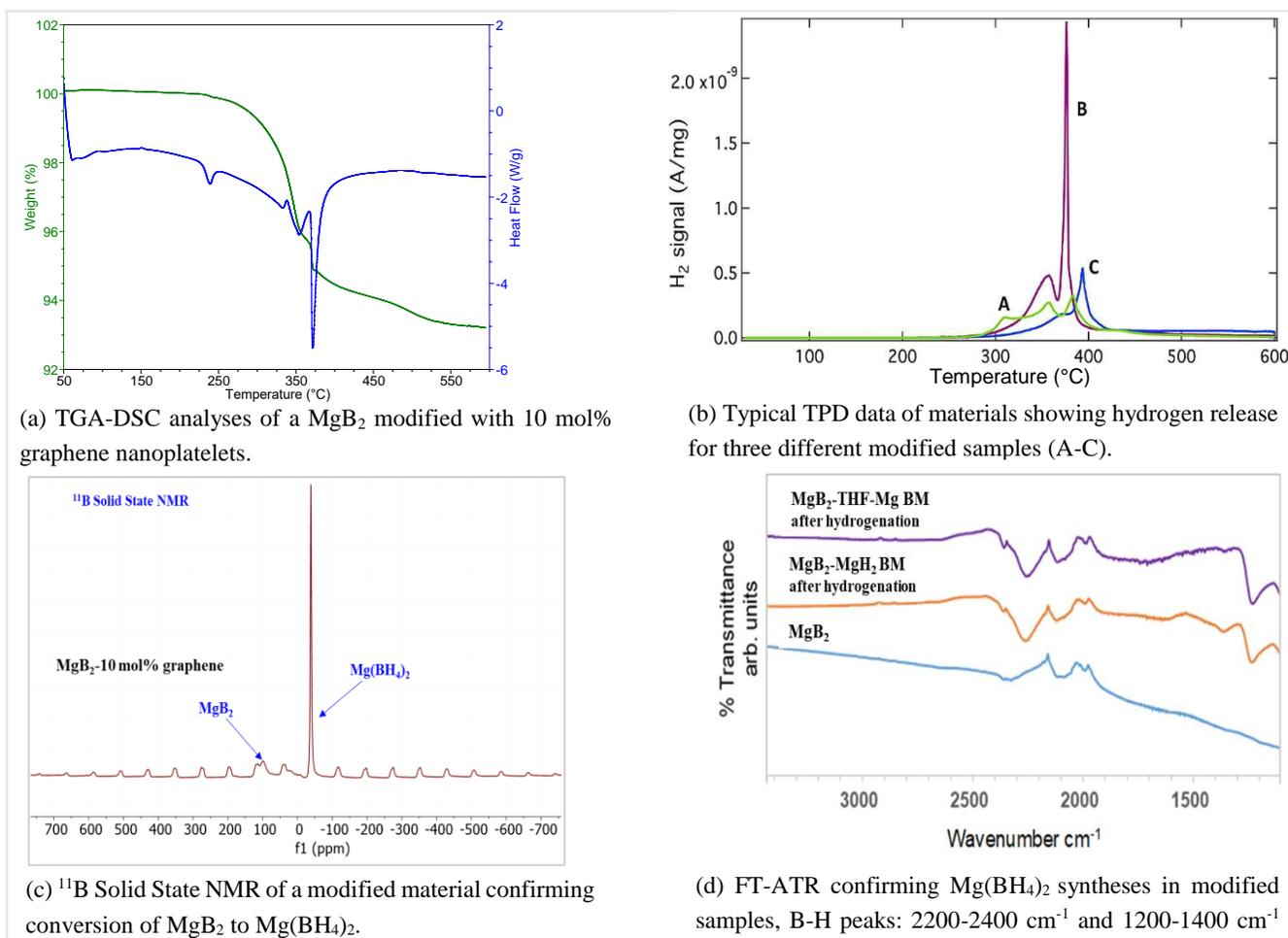


Figure 4. Typical characterizations of modified  $\text{MgB}_2$  materials hydrogenated at  $\leq 700$  bar and  $\leq 300$  °C; (a) TGA-DSC, (b) TPD (c) NMR and (d) FTIR.

the MgB<sub>2</sub> after hydrogenation process. The TPD analyses indicates only trace amounts of gas impurities during dehydrogenation of the materials. Table 1 provides a summary of the progression of gravimetric hydrogen densities and percent conversion of the modified MgB<sub>2</sub> materials from the inception of the project.

The continuous improvement of the hydrogenation conditions of MgB<sub>2</sub> from the state of art 900 bar and 400 °C to now 160 bar and 250 °C shows the plausibility of continuously improving the hydrogenation kinetics of the MgB<sub>2</sub> to Mg(BH<sub>4</sub>)<sub>2</sub>, to conditions relevant for onboard hydrogen storage.

A peer reviewed, journal cover article on discovery of additives for enhancing MgB<sub>2</sub> hydrogenation kinetics has resulted from this work.

*Funding Source:* U.S. Department of Energy, EERE; Energy Systems Development Special Fund

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*Last Updated:* October 2020

Bulk MgB <sub>2</sub> Hydrogenation	State of Art [Pure MgB <sub>2</sub> ]	Period 1 [modified MgB <sub>2</sub> ]	Period 2 [modified MgB <sub>2</sub> ]	Period 3 [modified MgB <sub>2</sub> ]	Period 3 [modified MgB <sub>2</sub> ]
Pressure/ bar	950	700	400	400	160
Temperature/ °C	~400	300	300	300	250
Wt % hydrogen	11 wt % (Sieverts)	7-8 wt % (TPD)		4-6 wt% (TPD)	~1 wt% (TGA)
% Conversion: MgB <sub>2</sub> to Mg(BH <sub>4</sub> ) <sub>2</sub>	75 % [Sieverts method: wt% H <sub>2</sub> ]	71 % [ <sup>11</sup> B solid state NMR line fitting method]	46 % [ <sup>11</sup> B solid state NMR line fitting method]	85 % [ <sup>11</sup> B solid state NMR line fitting method]	

Table 1. Our research shows plausibility of continuously improving the MgB<sub>2</sub> hydrogenation to Mg(BH<sub>4</sub>)<sub>2</sub>, to fuel cell technology relevant pressures and temperatures.

## ADDITIONAL PROJECT RELATED LINKS

### TECHNICAL REPORTS:

- 2020, [HyMARC Seedling: Development of Magnesium Boride Etherates as Hydrogen Storage Materials](#), G. Severa, C. Jensen, C. Sugai, S. Kim, 2019 DOE Hydrogen and Fuel Cells Program, Annual Progress Report to the U.S. Department of Energy for Contract Number DE-EE0007654.
- 2019, [HyMARC Seedling: Development of Magnesium Boride Etherates as Hydrogen Storage Materials](#), G. Severa, C. Jensen, C. Sugai, S. Kim, 2018 DOE Hydrogen and Fuel Cells Program, Annual Progress Report to the U.S. Department of Energy for Contract Number DE-EE0007654.
- 2018, [HyMARC Seedling: Development of Magnesium Boride Etherates as Hydrogen Storage Materials](#), G. Severa, C. Jensen, C. Sugai, S. Kim, 2017 DOE Hydrogen and Fuel Cells Program, Annual Progress Report to the U.S. Department of Energy for Contract Number DE-EE0007654.

### PAPERS AND PROCEEDINGS:

- 2019, C. Sugai, S. Kim, G. Severa, J. L. White, N. Leick, M. B. Martinez, T. Gennett, V. Stavila, and C. Jensen, [Kinetic Enhancement of Direct Hydrogenation of MgB<sub>2</sub> to Mg\(BH<sub>4</sub>\)<sub>2</sub> upon Mechanical Milling with THF, MgH<sub>2</sub>, and/or Mg](#), ChemPhysChem, Vol. 20, pp. 1-5.



**OBJECTIVE AND SIGNIFICANCE:** The objective of this project is to obtain key information that can be used for the development of a comprehensive, multi-scale computational model of reversible hydrogenation of magnesium boride, MgB<sub>2</sub> to magnesium borohydride, Mg(BH<sub>4</sub>)<sub>2</sub>. If successful, the project will significantly accelerate the discovery of boride materials for practical hydrogen storage applications. The project provides excellent training on state-of-the-art instrumentation to the participating UH graduate students, postdoc fellows, and early career scientists and enhances research competitiveness at UH by strengthening ties with U.S. national laboratories.

**BACKGROUND:** The magnesium boride/magnesium borohydride (MgB<sub>2</sub>/Mg(BH<sub>4</sub>)<sub>2</sub>) material system is one of the few cyclable materials that has a demonstrated gravimetric hydrogen storage capacity greater than 11 wt% and hence has a potential to be utilized in a hydrogen storage system that meets U.S. DOE hydrogen storage targets. This project works towards obtaining experimental information of 1) the bulk, nano-scale, and meso-scale structural changes occurring at elevated pressure following mechano-chemical modification of MgB<sub>2</sub>; 2) the reaction pathway of the reversible hydrogenation of MgB<sub>2</sub> to Mg(BH<sub>4</sub>)<sub>2</sub>; 3) the effect of elevated pressure and mechano-chemical modification on the chemical reaction pathways; 4) the interactions at solid-gas interfaces and particle surfaces; and 5) the kinetics and thermodynamic parameters associated with each step of the hydrogenation reaction pathway. The fundamental experimental information derived from the project will be used for the development of a comprehensive, multi-scale computational model of reversible hydrogenation of MgB<sub>2</sub> to Mg(BH<sub>4</sub>)<sub>2</sub> at the Lawrence Livermore National Laboratory.

This EPSCoR project is a collaborative effort between UH (HNEI, Mechanical Engineering (ME), Department of Chemistry, and Hawai'i Institute of Geophysics (HIGP)) and the National Renewable Energy Laboratory (NREL). The HNEI effort is focused on Vibrational and Raman Spectroscopy studies of modified MgB<sub>2</sub>, as well as Calorimetry studies of the initial stages of hydrogen uptake.

**PROJECT STATUS/RESULTS:** We have prepared ball milled samples of pure magnesium boride and MgB<sub>2</sub> containing various modifiers, and performed *in-situ* hydrogenation studies of the samples using Diffuse Reflectance Infrared Fourier Transform Spectroscopy (DRIFTS) in collaboration NREL. The purpose of the DRIFTS studies is to provide insights into the initial steps involved in the hydrogenation of modified MgB<sub>2</sub> materials. We are also probing the presence of B-H, Mg-H, and unanticipated bonding in the hydrogenated materials. The DRIFTS spectra of the modified MgB<sub>2</sub> samples indicate two unique overlapping vibrational peaks in the 1200-1400 cm<sup>-1</sup> region, that increase in intensity with hydrogenation temperature (Figure 1). These new broad peaks can be observed to varying degrees in the modified samples between 180-350 °C, hence are attributed to hydrogen interaction with the MgB<sub>2</sub>. Comparison of the relative intensities of the 1200-1400 cm<sup>-1</sup> features suggest that the anthracene and Mg-THF additives lead to the highest surface hydrogen uptake at these low hydrogen pressure conditions. We are currently ascertaining whether the vibrational peaks observed at 1200-1400 cm<sup>-1</sup> are due to B-H-B bond formation during the initial stages of hydrogen uptake. Furthermore, Raman studies are underway to assist in correlating the changes in boron-boron bonding occurring following mechano-chemical modification of MgB<sub>2</sub>, to the extent of hydrogen uptake.

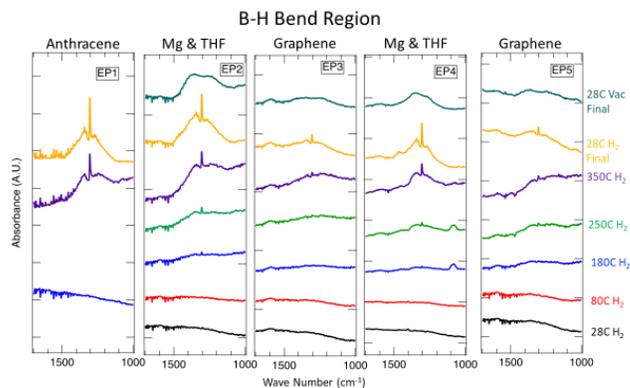


Figure 1. Summary DRIFTS spectra of modified MgB<sub>2</sub> materials in the B-H bend region showing presence of new peak at 1200-1400 cm<sup>-1</sup> during hydrogenation.

**Funding Source:** U.S. Department of Energy, EPSCoR

**Contact:** Godwin Severa, [severa@hawaii.edu](mailto:severa@hawaii.edu)

**Last Updated:** October 2020



### F1: Seawater Air Conditioning Environmental Monitoring

**OBJECTIVE AND SIGNIFICANCE:** The objective of this research is to develop a thorough understanding of the baseline oceanographic conditions at the proposed site of the Honolulu Seawater Air Conditioning (SWAC) system, and ultimately to use these data to assess the environmental impacts of the operation of the SWAC system. The district-scale system will be the largest of its kind in a tropical environment.

**BACKGROUND:** Seawater air conditioning is a type of renewable energy that utilizes deep, cold seawater in a heat-exchange system to cool a freshwater loop. The cold fresh water will then circulate to buildings and act as air conditioning coolant, thereby providing nearly carbon-neutral air conditioning. After the deep seawater is warmed in the heat exchange process, it will be released back to the ocean via diffuser.

In the proposed Honolulu SWAC system, deep seawater will be drawn from 500 m and released via diffuser at 100-140 m. Seawater at 500 m has significantly different characteristics than seawater at the diffuser depth, including nutrient concentrations that are higher by several orders of magnitude. The input of high-nutrient water could cause changes in food web dynamics.

**PROJECT STATUS/RESULTS:** Since 2012, we have characterized the oceanographic environment with deployments of long-term moorings, water column profiles, and water samples at both the intake (500 m) and proposed release (100-140 m) locations. Results have indicated that the plume of high-nutrient deep seawater *may* sink below the lit region of the ocean where phytoplankton grow (photic zone), reducing the potential environmental impacts. However, the depth of the plume release is at an area of rapid density change, and it is also possible that the plume may spread horizontally along the density surface and remain near the base of the photic layer. During strong wind events, deep mixing may bring the nutrient-rich water into the shallow photic zone, creating the possibility of a phytoplankton blooms (Comfort, 2015). Observations of the mesopelagic boundary community's daily across-slope migration indicated that the mid-trophic level organisms of this ecosystem will interact directly with the plume waters during their daily migration (Comfort, 2017).

Currently, monitoring efforts are ongoing and the temporal and spatial dynamics of phytoplankton at the proposed SWAC site are being investigated. Cell count data reveal higher concentrations of *Synechococcus* and lower *Prochlorococcus* at the nearshore release site than offshore near the intake site, which could be related to island effects of light availability and nutrients in the upper water column. We are currently characterizing the seasonality of phytoplankton which will provide the necessary baseline to assess if the operation of SWAC alters concentrations beyond natural fluctuations. Nutrients and phytoplankton counts were tightly correlated, suggesting that an input of nutrients from deep water to the photic zone from the SWAC system would alter the plankton dynamics of the region.



This project has produced the following publications:

- 2017, C.M Comfort, et al., [Observations of the Hawaiian Mesopelagic Boundary Community in Daytime and Nighttime Habitats Using Estimated Backscatter](#), AIMS Geosciences, Vol. 3, Issue 3, pp. 304-326.
- 2015, C.M. Comfort, et al., [Environmental Properties of Coastal Waters in Mamala Bay, O'ahu, Hawai'i, at the Future Site of a Seawater Air Conditioning Outfall](#), Oceanography, Vol. 28, Issue 2, pp. 230-239.

*Funding Source:* Office of Naval Research; Energy Systems Development Special Fund

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*Last Updated:* November 2020



**OBJECTIVE AND SIGNIFICANCE:** The goal of this research project is to develop and demonstrate a building energy analysis process that can be used during early design phases at multiple transit-oriented development (TOD) sites located along O‘ahu’s light rail line. This helps Hawai‘i meet its clean energy goals; through reduced energy use in buildings, increased energy security and resiliency, and a better quality of life for residents.

**BACKGROUND:** HNEI has worked closely over the years with the University of Hawai‘i’s School of Architecture’s Environmental Research and Design Lab (ERDL) to conduct energy efficiency research. Under this project, ERDL is collaborating with the University of Hawai‘i’s Community Design Center (UHCDC), the developers of multi-family residential building conceptual designs for the State Office of Planning in a project called the “Waipahu Transit Oriented Development Collaboration: Proof of Concept Research, Planning, and Design Study.”

At the start of this project, the Center’s current TOD planning process did not include quantitative targets for building energy use or for on-site renewable energy generation. Design teams lacked specific guidance to design beyond the building energy code. ERDL is collaborating with the UHCDC to bridge these gaps by providing energy efficient design processes and natural daylighting strategies.

The results of this process are intended to inform designers, developers, and the State with specific guidance on which building features will provide the biggest impact on the energy performance, peak loads, energy cost, building operating emissions, and annual energy consumption.

The team set out to create a whole-building energy model representative of future development of five-story multi-family buildings in Waipahu, Hawai‘i of approximately 20,000ft<sup>2</sup>.

In addition to the energy analysis, the team conducted detailed thermal comfort modeling to evaluate the applicability of passive cooling and/or mixed mode operation of the air conditioning systems in the residential units. The thermal comfort modeling considered both current and future weather

predictions associated with various climate change projections.



Figure 1. TOD Site, Waipahu. (Photo Credit: UHCDC)

#### **PROJECT STATUS/RESULTS:**

**Benchmarks:** Based on existing benchmarks, new condo/multifamily projects designed and built to the current energy code (IECC 2015) perform similar to many existing condo/multifamily developments in Hawai‘i. The energy simulations show that:

1. Designing to the IECC 2015 code can be achieved without additional effort and designers/building operators have the tools to achieve built performance; and
2. Driving building energy consumption down will take more than code minimum design.

The impact of combining various packages of energy conservation measures are described below. For additional detail, please refer to the final project report (linked on the following page).

**Baseline Modeling:** Using computer simulation and modeling, the team identified air conditioning (AC), domestic hot water, lighting, and equipment as the major energy end uses in a condo/multifamily residential building making them appropriate targets for advanced design.

**Energy Analysis:** The team demonstrated that building with air conditioning can be designed to reduce annual energy use by 29-61% compared to an IECC 2015 code minimum building.

The team modeled thousands of combinations of energy and design features that include building envelope and internal occupant loads. In addition to AC, domestic hot water and lighting, occupant plug loads, ventilation, window-to-wall ratio/glass, and glazing types were the biggest factors that influence energy performance.

**Net Zero Energy (NZE) Targets:** Buildings that are 2 stories or less can meet NZE targets. Taller buildings (over 3 or 4 stories) designed to IECC 2015 code minimum prescriptive requirements cannot achieve NZE due to insufficient roof area. In order for high density buildings to meet the NZE goal, off-site solar generation is needed.

**Peak Cooling:** Peak cooling demand can be reduced by providing minimum ventilation, effective building orientation, reduction of window area, increased exterior shading of windows, and use of high performance glass.

**Peak Electrical Demand:** Peak electrical demand can be reduced by not installing AC or using high efficiency AC when installed, with lower window-to-wall ratio, higher shading ratio, and better window performance. Photovoltaic panels and on-site battery storage can shave the peak electrical demand.

**Thermal Comfort:** Historic climate data shows that comfort can be achieved without mechanical cooling. With ceiling fans and air movement, thermal comfort can be increased to 96.4% of the year (based on the ASHRAE 55 adaptive thermal comfort benchmark). For reference, a typical conditioned office space is considered properly designed when comfort targets are achieved 98% of the year.

Even under optimistic future weather scenarios where global temperature rise is muted (through reduction in global greenhouse gas emissions), the passively cooled space in Hawai'i will struggle to meet an acceptable level of comfort throughout the year (more than 90% comfortable). We would encourage developers and designers to design for passive cooling and provide provisions for future installation of AC. The findings may also encourage the State to consider more stringent energy targets which would mitigate climate change and decrease the need for future AC.

The final project report “[University of Hawai'i Whole-Building Energy Modeling for Future TOD Areas](#)” provides guidance to architects, engineers, and professional designers in sufficient detail to allow the methodologies be replicated when designing future buildings in Hawai'i.

*Funding Source:* Energy Systems Development Special Fund

*Contact:* Jim Maskrey, [maskrey2@hawaii.edu](mailto:maskrey2@hawaii.edu)

*Last Updated:* November 2020



**OBJECTIVE AND SIGNIFICANCE:** The objective of this collaboration between the School of Architecture's Environmental Research and Design Lab (ERDL) and the Hawai'i Natural Energy Institute (HNEI) is to provide technical support to the Department of Hawaiian Home Lands (DHHL) and two sets of their design/builders (Gentry; Habitat for Humanity using a Honsador packaged design) to improve comfort and energy efficiency of homes built in their neighborhoods. The lessons learned can be applied to future houses constructed in this climate zone offering the opportunity to further reduce Hawai'i's dependence on imported oil and reduce greenhouse gas emissions.

Specific objective included:

1. Characterize the energy performance of typical single-family homes built on lands administered by DHHL.
2. Evaluate Building Energy Optimization Tool (BEopt) software for its ability to estimate relative performance of design options in terms of site and source energy use, greenhouse gas emissions, and thermal comfort.
3. Evaluate the ease of use of performance simulations for detached residential design as a flexible compliance pathway for the new Hawai'i State Energy Code based on International Energy Conservation (IECC) 2015 and create models that are minimally compliant to this code for the three DHHL house types.
4. Calibrate the computational models against the actual monitored energy use and temperatures gathered from the existing houses.
5. Identify and quantify potential future design strategies to exceed the new energy code and improve thermal comfort.
6. Estimate the size of a photovoltaic array that would achieve net-zero site energy.
7. Communicate these design strategies to DHHL, the designers, and the builders for consideration in future thousands of homes planned for development.
8. Train advanced-level architecture and engineering students, who are the design professionals of tomorrow in building monitoring, data analysis, and computer building performance simulation.

**BACKGROUND:** A key function of DHHL is to facilitate housing for native Hawaiian beneficiaries. In the past 20 years, DHHL has built over 2,590 homes. It currently owns over 200,000 acres of land on which it plans to construct another 875 homes over the next 5 years. DHHL is the only housing developer in Hawai'i dedicated to providing new homes to Hawaiian families. Historically, the homes have been adequate and affordable, but DHHL has not provided aggressive standards for building performance beyond code and there has been no post-occupancy work done to evaluate the energy performance or the level of occupant comfort in the various house types that have been constructed and occupied.

This study demonstrates how to improve the design of three typical house types in Hawai'i: fully air-conditioned, partially air-conditioned, and naturally ventilated (no air-conditioning). It was conducted from June 2017 to April 2019 and consisted of three components: monitoring existing houses; creating energy simulation models; and making design recommendations. The monitored houses, located in the DHHL neighborhood of Kaneheli in Kapolei, O'ahu, were built between 2009 and 2017, when the Hawai'i energy code was based on the IECC 2006 energy code. A team of researchers at ERDL used construction documents, field notes, and other information to create energy simulation models of the three house types. The houses were sub-metered for a year and the data were used to validate the energy models. These three existing-house models were modified to be minimally compliant to the new Hawai'i energy code based on IECC 2015. Some features were upgraded and others were downgraded to minimally meet the code.

Three existing house types were studied: centrally air-conditioned; partially air-conditioned; and naturally ventilated (no air-conditioning). For each house type, whole building energy models representing the following cases were compared: 1) existing house; 2) house minimally compliant with IECC 2015; 3) sensitivity studies for individual design variables; 4) house with combined energy efficiency measures; and 5) house with on-site renewable energy generation for net-zero energy performance.

The IECC 2015 models were used as a baseline to compare how different energy conservation measures

(ECMs) would individually affect the predicted annual energy consumption. A combination of ECMs were then selected by the research team to create a “combined strategy” model for each house type. The simulation models for the naturally ventilated house were also assessed for thermal comfort.

**PROJECT STATUS:** This project was substantially completed by November 2019, although dissemination of the results continued into 2020 with:

- Preparation of an abbreviated summary of results targeting architects and design professionals, and;
- Preparation of peer reviewed paper “[Going Beyond Code: Monitoring Disaggregated Energy and Modeling Detached Houses in Hawai‘i](#)”, published in the *Buildings* journal.

Overall, this initiative successfully:

- Trained UH system students in energy monitoring and building simulation;
- Resulted in quantified recommendations for design and operation of high-performance and net-zero site-built and packaged housing units;
- Quantified the savings from energy efficient and net zero options for 1,000 site-built and packaged homes, and;
- Developed building simulation models to evaluate multiple building scenarios.

Additionally, the investigation into the energy consumption of typical DHHL building types has benefits for the general understanding of residential building strategies in Hawai‘i and this climate zone and supports DHHL’s mission of providing affordable housing over its full life-cycle.

**SUMMARY RESULTS:** In a hot and humid climate, thermal comfort is a major driver in determining the energy consumption of a home and the satisfaction of the occupants. For fully air-conditioned homes, cooling is the single largest end-use of energy: 40% to 54% of annual consumption for homes in this study. For naturally ventilated homes, improving thermal comfort will improve the occupants’ experience and reduce the likelihood that air-conditioning will be retrofitted into the house.

Based on the parametric analyses, the team selected the energy efficiency measures at the point of

diminishing returns and anticipated acceptability by builders and residents. These were inputs to an energy model named “Combined Measures” for each house type. The selected measures and their individual and combined annual energy reductions as compared to the IECC 2015 base case are listed below.

The results of this study was summarized in the technical report “[Methods for Establishing and Validating Architectural Models to Analyze Building Performance of Existing Conditions and Simulated Design Options for Three Department of Hawaiian Homeland Residential Buildings in Kapolei, O‘ahu, Hawai‘i](#)”.

*Additional project summary sources: School of Architecture Environmental Research and Design Lab*

*Funding Source: Energy Systems Development Special Fund*

*Contact: Jim Maskrey, [maskrey2@hawaii.edu](mailto:maskrey2@hawaii.edu)*

*Last Updated: November 2020*



# Hawai'i Natural Energy Institute Research Highlights

## Appendix F: Energy Efficiency

### F4: Project FROG Net Zero, Mixed Mode Buildings

**OBJECTIVE AND SIGNIFICANCE:** The objective of this multi-year project is to understand energy performance and operation of net zero energy, mixed mode buildings in tropical climate and to use the buildings as real-world research facilities for the study of energy efficient building features and control strategies. The specific objectives of the current work are to measure and evaluate indoor air quality, particularly CO<sub>2</sub>, in manually operated mixed mode buildings. High levels of CO<sub>2</sub> can cause drowsiness, absenteeism, and poorer student performance.

**BACKGROUND:** Two unique energy efficient, net zero energy buildings constructed on the University of Hawai'i Mānoa campus serve as platforms for energy, comfort, and controls strategy research. Since 2016, HNEI has been extensively monitoring these mixed-mode Project FROG structures to gain insight into their performance.

The buildings were designed to be naturally ventilated with openable windows that allows air to flow through the room.

On-Demand HVAC control prevents the room from being air conditioned continuously at night or when classroom capacity factor is below 60% during the day. With the adjustable ceiling fans, the mixed mode buildings are comfortable for most of the year without the air conditioning running. The buildings are also outfitted with photovoltaic systems that generate more power than they consume.

The current research focuses on observing and characterizing CO<sub>2</sub> levels in the mixed mode buildings and understanding the influence of window operation. As part of this project, HNEI developed a sensor providing the building occupants real-time feedback on CO<sub>2</sub> levels, including a cue to take action to increase fresh air.

From an energy perspective, these buildings serve as models for energy efficient construction with highly insulated roof and walls, high performance low E glazing, ceiling fans, LED lighting with daylight controls, and orientation to prevent solar heat gain through the windows.

In addition, the research platforms serve as beta test sites for innovative controls and sensor research experiments including:

- Real time CO<sub>2</sub> indicators
- Automated ceiling fan controls
- Innovative occupancy sensing device
- Unique hi-res energy monitoring system
- Unique power quality monitoring system
- Deployed a thermal comfort perception kiosk

**PROJECT STATUS/RESULTS:** The Project FROG buildings continue to serve as functioning classrooms for both high school and university classes. In this ongoing project, we observed that CO<sub>2</sub> levels can exceed recommended levels, occasionally by a factor of two. User awareness and training are imperative to properly operate in the mixed mode. Building decisions are made every day by the instructors that impact the indoor air quality of a mixed mode building. Operation of windows, ceiling fans, and air conditioning are judiciously used to create healthy indoor air quality.

This project will be completed in December 2020.



Figure 1. UH Mānoa Project FROG buildings.

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*Last Updated:* October 2020

## **ADDITIONAL PROJECT RELATED LINKS**

### **TECHNICAL REPORTS:**

1. [Net Zero Energy Test Platform Performance Comprehensive Analysis](#), MKThink, March 2016

### **PAPERS AND PROCEEDINGS:**

1. 2020, S. Cerri, A. Maskrey, E. Peppard, [Retaining a healthy indoor environment in on-demand mixed-mode classrooms](#), Developments in the Built Environment, Vol. 4, Paper 100031. (Open Access: [PDF](#))
2. 2018, A.J. Maskrey, S. Cerri, E. Peppard, [Second Generation ZNE: Inheriting the Good Genes](#), Proceeding of ACEEE Summer Study on Energy Efficiency in Buildings Conference, Panel 10: Net Zero: Moving Beyond 1%, Article 10.
3. 2016, A.J. Maskrey, S. Cerri, E. Peppard, M. Miller, S. Uddenberg, [Positively net zero: case study of performance simulation and hitting the targets](#), Proceeding of the ACEEE Summer Study on Energy Efficiency in Buildings Conference, Panel 10: Net Zero, Net Positive, Article 10-1001.

### **PRESENTATIONS:**

1. 2018, A.J. Maskrey, S. Cerri, E. Peppard, [Next Generation ZNE: Inheriting the Good Genes](#), Presented at the ACEEE Summer Study on Energy Efficiency in Buildings, Panel 10: Net Zero: Moving Beyond 1%, Pacific Grove, California, August 12-17.



# Hawai'i Natural Energy Institute Research Highlights

## Appendix F: Energy Efficiency

### F5: Adaptive Lighting and Energy Efficient Security Strategy

**OBJECTIVE AND SIGNIFICANCE:** The objective of this project is to develop and test an adaptive lighting system, based on novel Light Detection and Ranging (LIDAR) sensor, that has the potential to significantly enhance security and dramatically reduce energy use and maintenance costs in high-security Naval installations.

**BACKGROUND:** The adaptive lighting project is a collaboration between HNEI, the California Lighting and Technology Center (CLTC) at University of California, Davis, and the Navy Facilities Engineering Command (NAVFAC) Hawai'i. Adaptive Lighting is the term describing a wide range of lighting solutions that adjust to changing environmental conditions, indoor or out. Adaptive lighting intensity can rise and fall with ambient light and occupancy while color rendering index and temperature can be adjusted to conditions defined by the end-use criteria.

In order to provide proof-of-concept and gain wider acceptance, this demonstration project will study the design, deployment, and impact of a unique wireless networked adaptive lighting solution for exterior lighting. Traditional security lighting, with long hours of uniformity, wastes energy unnecessarily and may reduce the security effectiveness in some applications. Sensor-based dynamic lighting adds conspicuous visual cues to enhance security effectiveness. Adaptive lighting can save from 50-70% of exterior lighting energy and has the potential to become an effective security measure as well.

**PROJECT STATUS/RESULTS:** In this research project, an adaptive lighting strategy is being piloted with exterior lighting fixtures on four O'ahu buildings – two NAVFAC buildings located on the Joint Base Pearl Harbor Hickam and two stand-alone classrooms at the University of Hawai'i at Mānoa (UHM). The exterior lighting levels will be variable, operating at full intensity when there is activity detected near the structures at night. With no motion detected, the fixtures will dim down to 30%, providing enough light for security purposes. LIDAR sensors send out laser signals that when reflected back trigger an action, specifically a signal to ramp the fixtures up to 100%. Sensors are positioned on these buildings to

create a 360 degree horizontal detection zone, sensitive to any motion that crosses the beam's path.

The second significant goal of this project is to test a wireless networking system that will synchronize the ramping up of all the fixtures simultaneously. When one sensor is triggered, all of the fixtures connected to the network will activate simultaneously. Not only does this prevent a visually annoying checkerboard effect with fixtures triggering at different times, but site security is improved with the visual "announcement" made when motion is detected and the lights ramp immediately up from dim to 100%.

The sensors and monitoring equipment collected data between January and July 2020. This data is currently being evaluated.

The project was originally contracted from January 2019 to June 2020, however, delays due to the coronavirus resulted in a no-cost extension to June 2021.



Figure 1. UHM FROGs with LIDAR sensor and fixtures.

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020



**OBJECTIVE AND SIGNIFICANCE:** The Thermal Comfort Portal (<http://hnei.hidoe-thermal-comfort.4dapt.com>) is a web-based research tool developed for the Hawai'i Department of Education (HIDOE) to provide resources for design and implementation of their heat abatement program. In addition to providing monitored climate and building data, the portal includes recommendations about heat abatement and thermal comfort strategies and solutions for consumer and professional use. Its objective is to expand program participation to the greater sustainable design community, who could offer abatement solutions during design and/or implementation of heat mitigation strategies.

**BACKGROUND:** Many of the public schools in Hawai'i do not have space conditioning, nor do they have access to weather data that could inform decisions about activities impacted by weather in school facilities. Under this project, the Hawai'i Natural Energy Institute (HNEI) is providing HIDOE with the technical resources and expertise to support the delivery of energy and weather data that enables researchers, the community, and design professionals to make data-driven decisions for designs and resource allocation.

Publicly released in November of 2017, HNEI has hosted the Thermal Comfort Portal as a research resource for microclimatic data across Hawai'i. Specific thermal performance of public schools are also available on the website. HNEI supports public participation and outreach by hosting the portal on its website. The design firms MKThink and Roundhouse One developed and constructed the Thermal Comfort Portal on behalf of the HIDOE and continue to provide back-end infrastructure support.

**PROJECT STATUS/RESULTS:** The HIDOE Thermal Comfort Portal continues to be supported on the HNEI website. HIDOE continues both its [Heat Abatement Program](#) as well as its Cool Classrooms air conditioning strategies.

This project is ongoing and HNEI's hosting of the portal will continue through December 2020.

*Funding Source:* Energy Systems Development Special Fund

*Contact:* Jim Maskrey, [maskrey2@hawaii.edu](mailto:maskrey2@hawaii.edu)

*Last Updated:* October 2020

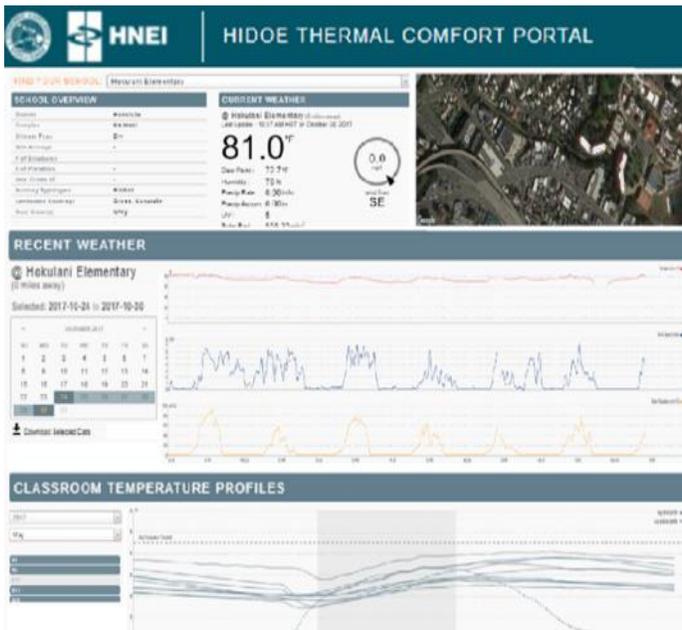


Figure 1. A screenshot of the Thermal Comfort Portal, showing HOKULANI ELEMENTARY's outdoor environmental data and classroom temperature data.

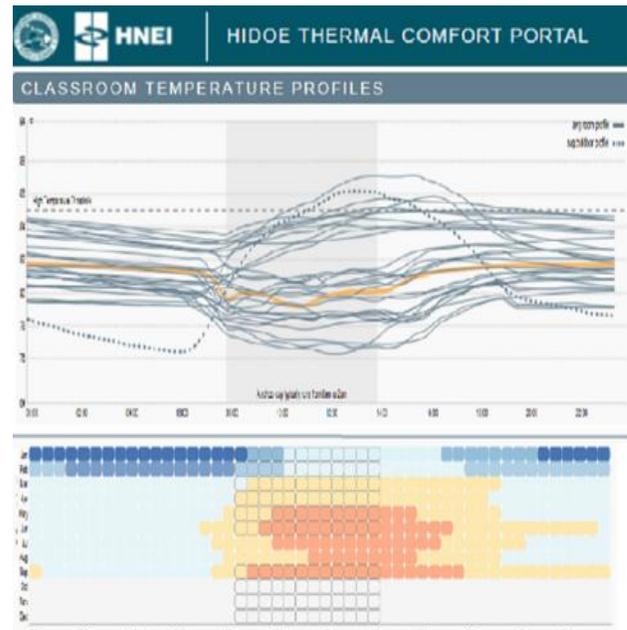


Figure 2. A screenshot of the Thermal Comfort Portal, showing HOKULANI ELEMENTARY's indoor temperature and outdoor temperature heat map.



# Hawai'i Natural Energy Institute Research Highlights

## Appendix G: Transportation

### G1: NELHA Hydrogen Station and Fuel Cell Electric Buses

**OBJECTIVE AND SIGNIFICANCE:** HNEI has installed a 65kg/day hydrogen production and dispensing station on the Island of Hawai'i at the Natural Energy Laboratory Hawai'i Authority (NELHA) (Figure 1). The objective of the project is to evaluate the technical and financial performance, and durability of the equipment, and support a fleet of three hydrogen Fuel Cell Electric Buses (FCEB) operated by the County of Hawai'i Mass Transit Agency (MTA). The knowledge gained in this project will inform the MTA on benefits and issues associated with transitioning from a diesel bus fleet to a zero emissions FCEB fleet in support of the State of Hawai'i's clean transportation goals. The knowledge will also be transferred to other counties to assist them in evaluating the deployment of zero emission buses for their public transportation fleets.



Figure 1: Hawai'i Hydrogen Station.

**BACKGROUND:** Development of hydrogen-based transportation systems requires hydrogen infrastructure to produce, compress, store, and deliver the hydrogen, a means to dispense the fuel, and vehicles capable of using high purity hydrogen. The HNEI hydrogen station at NELHA has been designed to dispense hydrogen at 350 bar (5,000 psi). Rather than use ground mounted permanent tank storage, HNEI will demonstrate centralized hydrogen production and distributed dispensing with a fleet of three hydrogen transport trailers (HTT). High purity hydrogen produced at the NELHA site will be delivered to the MTA base yard in Hilo to support deployment of heavy-duty FCEBs operated by the MTA Hele-On public bus service. The concept is illustrated in Figure 2.

In addition to the technical and cost analysis, HNEI is developing implementation plans to support the introduction of zero emission transportation systems. HNEI is coordinating with the University of Hawai'i's Hawai'i Community College supporting

the introduction of workforce development programs to train technicians to service the FCEBs and other battery electric vehicles.



Figure 2: Hydrogen Transport Concept.

### **PROJECT STATUS/RESULTS:**

#### **Hydrogen Station**



Figure 3: HNEI Hydrogen Station.

The site works as well as the hydrogen production and compression systems equipment have been installed at NELHA (Figure 3). The station is in the final stages of being commissioned by HNEI and Powertech, the equipment supplier. The station uses a Proton Onsite (now Nel) electrolyzer to produce 65 kg of hydrogen per day at an outlet pressure of 30 bar (440) psi. A HydroPac compressor (Figure 4) compresses the hydrogen to 450 bar (6,600 psi).



Figure 4: HydroPac Compressor.

The system is powered by the HELCO grid which includes a substantial fraction of renewable energy including solar, wind, and geothermal.

### ***Hydrogen Transport Trailers***

Three trailers (Figure 5) are available for transport between the production and fueling site. The trailers were recently hydrostatically tested, pressure and thermal relief safety valves were upgraded, and the trailers were recertified by the Federal Transit Administration for use on U.S. public roads. The hydrogen cylinders must be recertified every five years.



Figure 5: Hydrogen Transport Trailers.

### ***Hydrogen Dispensing System***

The dispensing system consists of a dispenser (Figure 6) connected to a fueling trailer through a fueling post interface (Figure 7) that is connected to the dispenser via an underground hydrogen piping distribution system. The hydrogen dispenser is fully automated and programmed to “fail safe” for unattended operation.



Figure 6: Hydrogen Dispenser.



Figure 7: NELHA Fueling Post Interface.

The fueling dispensers located at NELHA and at MTA are identical except for the addition of a boost compressor at the MTA site integrated into the MTA fueling post (Figure 8). The boost compressor system was developed by HNEI and Powertech to dispense up to 90% of the hydrogen stored in the HTT in order to reduce transportation costs by not having to return half-filled trailers to be refilled at NELHA.



Figure 8: MTA Boost Compressor Fueling Post.

### ***Hele-On 29-Passenger Fuel Cell Electric Bus***

The Hele-On 29-passenger FCEB (Figure 9) was purchased with funds from the Energy Systems Development Special Fund. This bus, manufactured by Eldorado National and converted to a hydrogen-electric drive train by U.S. Hybrid is ADA-compliant. The fuel cell power system was recently upgraded by replacing the original 30 kW Hydrogenics fuel cell with a new state-of-the-art 40 kW U.S. Hybrid fuel cell.



Figure 9: Hele-On 29-Passenger FCEB.

Onboard hydrogen is stored in composite carbon fiber cylinders located under the bus with a capacity of 20kg. The fuel cell power system is integrated with two 11 kWh A123 Lithium-ion battery packs to provide motive power to a 200 kW electric drive system. U.S. Hybrid also replaced batteries with the new technology A123 batteries using U.S. Hybrid internal funding. At cruising speed, the fuel cell maintains the battery state of charge within a range that supports the long-term health of the battery. During deceleration, the electric motor acts as a generator sending power back into the battery (“regenerative braking”). This contributes to overall system energy efficiency and improves bus mileage. The bus has a range of approximately 200 miles depending on the route topography and driver skills.

#### ***Bus Export Power Unit***

A 10 kW export power system (Figure 10) was installed in the 29-passenger bus to enable the bus to provide 110/220VAC electric power at full power for up to 30 hours as emergency power for civil defense resilience operations when the grid power is down. The bus can be refueled in 10 minutes providing an additional 30 hours of emergency power.



Figure 10: Bus Export Power Unit.

#### ***Hele-On 19-Passenger Fuel Cell Electric Buses***

Two 19-passenger FCEBs (Figure 11) were also acquired by the MTA from Hawai‘i Volcanoes National Park (HAVO). These buses were converted by U.S. Hybrid and are of similar design to the 29-passenger FCEB. Onboard hydrogen capacity is 10 kg giving a projected range of 100 miles. These buses are being upgraded with 40kW U.S. Hybrid fuel cells and A123 Lithium-ion batteries using funding from the County of Hawai‘i.



Figure 11: HAVO 19-Passenger FCEB

#### ***Publications***

This project has produced the following papers:

- 2020, A. Headley, G. Randolph, M. Virji, M. Ewan., [Valuation and cost reduction of behind-the-meter hydrogen production in Hawai‘i](#), MRS Energy & Sustainability, Vol. 7, Paper E26.
- 2020, M. Virji, G. Randolph, M. Ewan, R. Rocheleau. [Analyses of hydrogen energy system as a grid management tool for the Hawaiian Isles](#), International Journal of Hydrogen Energy, Vol. 45, Issue 15, pp. 8052-8066.

*Funding Sources:* U.S. Department of Energy; Office of Naval Research; NELHA; U.S. Hybrid; State of Hawai‘i Hydrogen Fund; County of Hawai‘i; Energy Systems Development Special Fund

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*Last Updated:* November 2020



### G2: Bi-Directional EV Charging Demonstration Project

**OBJECTIVE AND SIGNIFICANCE:** The main objective of this demonstration project is to develop and evaluate the performance of novel algorithms to optimize the charge/discharge of shared fleet vehicles. Project experience and results will inform University consideration of options such as the electrification of fleet vehicles, advanced car share applications, integration of distributed renewable energy resources on campus, and the optimal management of campus energy use and cost containment.

**BACKGROUND:** HNEI is collaborating with Hitachi Limited and IKS Co., Ltd. on a technology development, test, and demonstration project to install two bi-directional electric vehicle (EV) chargers (Hybrid-PCS on the campus of the University of Hawai'i at Mānoa, at two designated parking stalls indicated by the red rectangle in Figure 1, located adjacent to the Bachman Annex 6 building indicated by the orange rectangle in Figure 1.



Figure 1. Location of bi-directional EV chargers.

The new control algorithms will ensure that the shared vehicles are efficiently assigned and readily available for transport needs, while providing ancillary power and energy services by virtue of charging or use of the stored energy in the vehicle batteries to benefit both the customer (UH Mānoa) and possibly the operational needs of the local grid operator (Hawaiian Electric).

The two EVs will be used by designated university personnel through a limited-user pool car sharing system via a smart phone/web-based application made available to the drivers. The EVs are planned to replace the present use of two existing UH gasoline-powered vehicles for the duration of this multi-year demonstration.

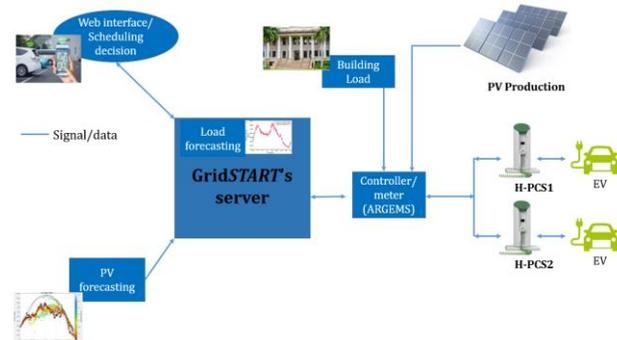


Figure 2. Functional system diagram.

This project is being conducted by HNEI's GridSTART team. The team is developing a web-based software suite for EV drivers to sign-out the cars for use and will design, code, and integrate software to optimize charge/discharge schedules for the EVs, balancing transport needs and power/energy benefits for the University (e.g., time-of use tariff rates, building load shaping, smart EV charging, etc.), and possibly grid ancillary services. The Hybrid-PCS can also incorporate solar PV power as a source of energy for EV charging. The optimization software will incorporate in-house developed state-of-the-art solar forecasts and maximization of solar energy as the preferred source for EV charging.

**PROJECT STATUS/RESULTS:** An EV has been purchased and HNEI has taken delivery of the first Hybrid-PCS for the project. Engineering design drawings for charger installation are complete. The procurement of construction services and equipment needed to install the bi-directional EV chargers on campus is underway. EV charge/discharge control algorithms and EV car scheduling software is under development, along with plans for hardware-in-the-loop testing of controls and communications. Delivery of the second Hybrid-PCS is expected in February 2021, with project installation and go-live to follow.

*Funding Source:* Office of Naval Research; Hitachi Advanced Clean Energy Corporation

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*Last Updated:* October 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix H: Ocean Energy

### H1: Research Support to the U.S. Navy Wave Energy Test Site

**OBJECTIVE AND SIGNIFICANCE:** Wave energy has enormous potential to address global renewable energy goals, yet it poses daunting challenges related to commercializing technologies that must produce cost-competitive electricity while surviving the energetic and corrosive marine environment. The nascent commercial wave energy sector is thus critically dependent on available test infrastructure to address these issues. To address this need, the U.S. Navy established the Wave Energy Test Site (WETS) in the waters off Marine Corps Base Hawai'i (shown below), the U.S.' first grid-connected site, completing the buildout in mid-2015. WETS consists of test berths at 30m, 60m, and 80m water depths and can host point absorber and oscillating water column devices to a peak power of 1 MW. HNEI provides key research support to this national effort in the form of environmental monitoring, independent wave energy conversion (WEC) device performance analysis, and critical marine logistical support. The results achieved at WETS will have far reaching impacts in terms of advancing wave energy globally.

Layout of Navy Wave Energy Test Site



**BACKGROUND:** Through a cooperative effort between the Navy and the U.S. Department of Energy (DOE), WETS hosts companies seeking to test their pre-commercial WEC devices in an operational setting. HNEI works with the Navy and DOE to directly support WEC testing at WETS in three key ways: 1) *environmental impact monitoring* – acoustic signature measurement and protected species monitoring, 2) *independent WEC device performance analysis* – including wave forecasting and monitoring, power matrix development (power output versus wave height and period), numerical hydrodynamic modeling, and a regimen of regular WEC and mooring inspections, and 3) *logistics support* – in the form of past funding to modify a site-

dedicated support vessel for use at WETS, through local partner Sea Engineering, Inc., assisting WEC developers with deployment planning, and through funding to developers for maintenance actions. While the US DOE funding and cost share from the ESDSF have been fully expended, the project is continuing with funding from the Naval Facilities Engineering Command.

**PROJECT STATUS/RESULTS:** Since mid-2015, the major activities have occurred at WETS, with HNEI in both supporting and leading roles. These are summarized in the series of figures below.

*June 2015 to December 2016:* Northwest Energy Innovations (NWEI) deployed Azura device at 30m berth.



*March 2016 to April 2017:* Sound and Sea Technology deployed Fred. Olsen Lifesaver at 60m berth. This project was not grid-connected.



*February to August 2018:* HNEI led second deployment of Azura, with modifications designed to improve power performance, including enlarging the float and adding a heave plate at the base.



*May to June 2019:* Led major redesign and reinstallation effort for the WETS deep berth moorings. 60m berth reinstalled, with 80m berth reinstallation planned for spring/summer 2021.



*October 2018 to March 2019:* HNEI led effort to redeploy Lifesaver, at 30m, with modifications to moorings and integration of UW sensor package and subsea charging capability, which drew its power from the WEC itself. This use of wave energy to power an offshore sensing suite was an important national first.



*November 2019:* Completion of site-dedicated support vessel Kupa'a, by research partner Sea Engineering, Inc. This vessel adds significantly to our ability to perform various functions at WETS.



At this update, additional activities planned in the coming year include:

- 1) Deployment of the C-Power SeaRay WEC. This will be a stand-alone (not grid-connected) deployment of a small, 1kW device that will feed power to a subsea acoustic sensing system from the company Biosonics.
- 2) Deployment of the Oscilla Power Triton-C WEC at the 30m berth.
- 3) Repairs to the 80m berth.
- 4) Deployment of the Ocean Energy OE35 WEC at the 60m berth. The OE35, pictured below, is a large oscillating water column device currently on site in Hawai'i.



Looking ahead to 2022 and 2023, we expect WEC deployments from C-Power (a larger device called StingRay), Northwest Energy Innovations (a much larger version of Azura), and Aquaharmonics, as well as ongoing WEC and infrastructure inspections, maintenance and repairs, acoustic data collection, wave measurement and forecasting, hydrodynamic analysis of WEC performance and mooring fatigue, and other activities in support of DOE, Navy, and developer test objectives at WETS.

*Funding Sources:* Naval Facilities Engineering Command; U.S. Department of Energy; Office of Naval Research; Energy Systems Development Special Fund

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*Last Updated:* November 2020



### H2: The Hawai'i Wave Surge Energy Converter (HAWSEC)

**OBJECTIVE AND SIGNIFICANCE:** The project described here was recently selected for funding by DOE's Water Power Technologies Office and builds on this growing expertise in the nascent field of wave energy to develop our own WEC concept – from conception through numerical modeling at two scales and testing in mainland tank facilities at each scale. The objective is to mature a WEC concept that can ultimately produce cost-effective renewably generated electricity for coastal communities. Its inherent scalability could support smaller-scale generation for isolated communities or islands, or larger-scale devices (likely deployed in arrays) to generate power to feed into coastal power grids. The project, called the Hawai'i Wave Surge Energy Converter (HAWSEC), is expected to make important advances in the emerging wave energy field and has the potential to mature a technology with realizable commercial potential in the future – for Hawai'i, the U.S., and beyond.

**BACKGROUND:** HNEI has been involved in supporting research and testing objectives at the U.S. Navy's Wave Energy Test Site (WETS) off Marine Corps Base Hawai'i since 2010, with funds from both the U.S. Department of Energy (DOE) and the U.S. Navy (Naval Facilities Engineering Command – NAVFAC). This has involved providing environmental measurements, serving as an independent third-party assessor of wave energy converter (WEC) device power performance and survivability/maintenance issues, and providing key logistical support to WEC developers and DOE/Navy. Through this involvement, HNEI has gained valuable practical experience associated with real-world deployment and operation of WECs in this first-of-its-kind in the U.S. grid-connected test site. Additionally, through numerical modeling of WEC dynamics and mooring systems in support of WETS test objectives and WEC developers, HNEI has accumulated key design insights and numerical modeling experience related to WEC design.

The HAWSEC concept is based on the oscillating wave surge energy converter (OWSC), or flap-type, WEC. Such systems rely on the surge motion of the waves close to shorelines, where wave direction becomes more consistent than offshore. The flap moves back and forth in the waves and drives

hydraulic cylinders to pump water through a hydro turbine to generate electricity. A rendering of our conceptual flap is shown below. We will explore both a high-head/low-flow and a low-head/high-flow hydraulic system, utilizing the same flap, in the first half of the project, ultimately settling on an optimized configuration (with a hydro turbine selected to best align with the optimized head and flow) before scaling up for additional testing in the latter stages of the project.



Figure 1. Artist rendering of the HNEI HAWSEC system.

HAWSEC development will proceed along the following broad set of tasks:

- 1) Numerical modeling of small-scale version, nominally a 1m x 1m flap, to optimize design;
- 2) Fabrication and local testing of the small-scale system – both the hydraulic system and the flap itself in nearshore waters on O'ahu;
- 3) Controlled tank testing of the small-scale system at Oregon State University's (OSU) Hinsdale wave basin;
- 4) Validation of numerical modeling with test results from OSU;
- 5) Numerically scaling up to medium scale, nominally a 3m x 3m flap, and completing a buildable design of the HAWSEC at this scale;
- 6) Undergoing a Go/No-Go decision with DOE;
- 7) Fabrication of a full medium-scale system, including flap and hydraulics;
- 8) Controlled tank testing of the medium-scale device at the University of Maine's test flume; and

- 9) Validation of medium-scale numerical models with test data from Maine, and modeling and performance prediction for a full-scale version of HAWSEC.

**PROJECT STATUS/RESULTS:** This three-year project was initiated in August 2020. Significant progress has been made in the numerical modeling steps for the smaller-scale device, supporting key design decisions being made in advance of fabrication of the test article for this scale. We anticipate readiness for bench testing of our hydraulic system in March 2021, with in-ocean testing beginning in May 2021, and OSU tank testing in the August/September timeframe. This document will be updated over the course of the project to include key model results, photos of test articles, test tank results, and so on.

*Funding Source:* U.S. Department of Energy, Water Power Technologies Office; Energy Systems Development Special Fund

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*Last Updated:* November 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix I: International

### I1: Asia Pacific Regional Energy System Assessment

**BACKGROUND:** In August 2017, HNEI initiated efforts under a five-year grant from the Office of Naval Research (ONR) for the Asia Pacific Regional Energy System Assessment (APRESA). The objective of this five-year grant is to develop comprehensive energy system assessments that include strategy, policy, technology options, implementation plans, and training for energy system transitions in select locations throughout the Asia-Pacific region, based on the specific requirements or needs of the targeted jurisdictions and strategic alliances. The first three years of this program has laid a firm foundation for continued success built upon the development of solid partnerships with national, regional or local jurisdictions, private and public stakeholders including utilities, universities, and other research and international aid and development entities such as the Asian Development Bank (ADB), and U.S. Department of Defense (DOD) organizations in the areas of interest.

Active engagement and support activities are currently ongoing in Vietnam, Thailand, Laos, Indonesia, and the Philippines. Jurisdictions were selected based on projected demand growth and need for rapid energy system expansion and transformation, the potential to integrate renewable energy technologies, and collaborative environment in which to conduct the work.

In addition to the deep local partnerships formed in these jurisdictions, this program has led to a successful collaborative relationship with the U.S. Agency for International Development (USAID) and its implementing prime contractors throughout the region (e.g., Deloitte, Tetra Tech, Abt Associates, RTI, and Chemonics).

USAID partner country governments are in need of high-quality technical expertise to guide their decision making and can learn from the experience of more developed countries using their best practices and case studies. With significant experience providing technical expertise in the renewable energy space, HNEI is uniquely positioned to partner with USAID and provide energy intelligence in identifying tailored solutions for jurisdictions in need. This collaborative approach, leveraging the capabilities, resources and know-how of HNEI and USAID implementing contractors in the Asia-Pacific region,

is consistent with the U.S. whole-of-government strategy to grow sustainable and secure energy markets across the region. Achieving self-reliance enables emerging economies to rely less on external aid in times of crisis, promote more transparent markets that incentivize private investment, and redirects resources from inefficient energy subsidies toward more productive utilization. Low-cost renewable energy has the potential to improve the financial viability of energy sectors, reduce vulnerabilities to malign and climate change influences, and improve a country's overall ability to finance their self-reliance. HNEI's collaborations and interventions under this grant help deliver technical expertise to policymakers in emerging economies that can aid in achieving lower cost, cleaner energy solutions that catalyze competitive markets and reduce carbon emissions, ultimately enabling their populations to enjoy universal, reliable, and cleaner electricity services.

The activities summarized below are representative of the ongoing partnerships and efforts between HNEI and its Asia-Pacific Partners. While these efforts cut across a broad cross-section of HNEI activities, most are being spearheaded by HNEI's Grid Systems Technologies Advanced Research Team (GridSTART).

HNEI proposes to utilize continued APRESA funding to extend the efforts in the current countries and to expand this work to other countries, regions, and DOD facilities of interest. Included in this planned effort is support for Hawai'i Green Growth to assist the regional attainment of the UN Sustainability Goals.

**PROJECT STATUS/RESULTS:** A number of select projects initiated under the APRESA award are summarized below. Two of these are described in more detail in following Appendices (I2 and I3).

#### **EGAT Renewable Integration Study (Thailand)**

On February 28, 2018, the Electricity Generating Authority of Thailand (EGAT) held a ceremony to sign a multi-year Memorandum of Understanding (MOU) with HNEI. The MOU terms of reference include education, training, workshops, and exchange programs (study tours or site visits) under topics such as *Strengthening the Operation Capacity to Support*

*Renewable Energy Integration into the Power System.* Under this MOU, HNEI and EGAT initiated a renewable integration assessment of the Thai power system considering increasing levels of renewable energy resources. This work, described in more detail in Appendix I2, will continue under a new four-year term MOU effective May 20, 2020, extends and expands the collaborative work amongst HNEI and EGAT.

### **Vietnam: Mapping of Renewable Energy Sector Innovation System**

Under this project, HNEI is providing financial support and guidance, to the National Institute for Science and Technology Policy and Strategy Studies (NISTPASS) to map the innovation system in the renewable energy (RE) sector in Vietnam. While the development of renewable energy resources in Vietnam is a government priority, there is lack of clarity in regard to the role of many organizations in Vietnam impacting energy development and the relationship between them. One of the objectives of this work is to identify key stakeholders in the RE sector for further policy and institutional support. This work is described in more detail in Appendix I3.

### **Thailand: Biomass Gasification Demonstration**

With APRESA funding, HNEI is in the process of contracting with Chiang Mai Rajabhat University, Thailand, to conduct an assessment of small gasification systems as a firm power option in islanded settings. The study will include a resource assessment of potential biomass feedstocks in Thailand including urban solid wastes and agricultural residues and a technology assessment of available conversion systems. Based on these results, a conversion system will be selected and evaluated in an existing micro-grid operated at Chiang Mai Rajabhat University. These extended tests will evaluate feedstocks and their preparation, identify maintenance requirements and practices, develop gasifier system control strategies for interfacing with the intermittency of other micro-grid components.

In a related effort, APRESA funds have supported a postdoctoral fellow, Dr. Quang Vu Bach, who is participating in a research program evaluating sustainable aviation fuel production systems for tropical environments. Current activities include evaluation of biomass resources derived from urban

solid waste and their suitability as feedstocks for thermochemical gasification systems. The synthesis gas product can be subsequently converted with Fischer-Tropsch synthesis to sustainable aviation fuel. The aviation industry (civilian and military) faces significant greenhouse gas challenges due to dependence on petroleum jet fuels and limited opportunity for electrification.

### **Technical Support for Development of BESS Technical Standards for Thailand**

Propelled by the rapidly falling price for battery energy storage systems (BESS), there are increasing applications of BESS by end-users including utilities, industries, and homeowners. Despite the emergence of BESS applications in Thailand, there is still a lack of regulations to ensure the quality and safety of BESS installations and operations. The Office of Energy Regulatory Commission of Thailand (OERC) expressed its interest to USAID Clean Power Asia to develop regulations that address the engineering, performance, and safety of the installation and operation of BESS (BESS Technical Standards) as well as relevant electrical grid connection codes. Under USAID Clean Power Asia, Abt Associates subcontracted HNEI for its GridSTART to develop BESS Technical Standards and provide recommendations on electrical grid connection codes relevant to BESS.

### **ASEAN Interconnection Masterplan Study (AIMS) III Support**

As a basis for assessment, regional planning, and development of a prospective integrated ASEAN Power Grid, the ASEAN countries – led by the Head of ASEAN Power Utilities/Authorities (HAPUA) – have conducted *The ASEAN Interconnection Master Plan Study* (AIMS). Building upon this foundational work, the latest analysis (AIMS III) was initiated to evaluate ASEAN power market integration through the grid connection of renewable energy and power trade. The HNEI GridSTART team is offering technical assistance as a core member of the technical review group comprised of international experts to review and provide guidance on the scope, data collection, assumptions and execution of the AIMS III study.

### **ASEAN Centre for Energy (ACE) Capacity Building**

The ASEAN Centre for Energy (ACE), an intergovernmental organization within the ASEAN structure, represents the interests of the ten ASEAN Member States (AMS) in the energy sector. HNEI is delivering training at the request of ACE to build the knowledge base and capability of ACE planning/engineering staff in the advanced analytics needed for effective renewable energy integration and power grid modernization and optimization in ASEAN countries. In February 2020, training was provided on the need for, value, tools, and methodologies of production cost modeling and analytics. Further in depth training on renewable integration tools and methodologies are continuing. This training will enhance ACE's close work with energy authorities/ministries in the AMS in implementing the ASEAN Plan of Action for Energy Cooperation which serves as a blueprint for AMS cooperation to enhance energy development, while shaping the region's growth to be sustainable and environmentally friendly.

### **Recommendations on Methodology for Vietnam Power Development Plan (PDP)**

HNEI contributed to V-LEEP's report to Vietnam's MOIT/EREA on a new methodology roadmap to update the historical power development plan (PDP) process and to incorporate international best practices for planning for higher levels of variable renewable energy. The V-LEEP team (including members of HNEI's GridSTART team) conducted an assessment to identify the advantages and disadvantages of previous PDP preparation in Vietnam, the changes needed to be made, and the technical and institutional set-up requirements of agencies involved in preparation of the PDP. Based on the results of this assessment, MOIT/EREA has adopted V-LEEP's recommendations on a new process for PDP-8 preparation that includes specific steps and a roadmap for implementation.

### **Renewable Energy Integration Support in Vietnam**

In a joint effort with the USAID Greening the Grid (GtG) program, the Vietnam Low Emission Energy Programme (V-LEEP) under the leadership of Deloitte has been working closely with relevant agencies in Vietnam's Ministry of Industry and Trade

(MOIT), the Electricity and Renewable Energy Authority (EREA), Electricity Regulatory Authority of Vietnam (ERAV), and the Institute of Energy (IEVN) to study and enable a functional and competitive regulatory framework and conditions which support an increase of renewable energy generation and consumption. HNEI is partnered with the National Renewable Energy Laboratory (NREL) to support V-LEEP with expertise in variable renewable energy integration modeling and advanced power system planning for Vietnam's Power Development Plan (PDP-8) efforts.

### **Enhancing Customer Participation in the Philippines' Net-Metering Framework**

HNEI is providing technical and capacity building support in collaboration with USAID Clean Power Asia (USAID CPA) to assist the Philippines Department of Energy (PDOE) prepare its Department Circular (DC) for Promulgating Policies to Enhance Customers' Participation in the Philippines' Net-Metering Framework. In 2019, the HNEI GridSTART team delivered expert in-person training and messaging support at the request of the PDOE in public consultation meetings held in several major Philippine cities. Technical support to PDOE is continuing.

### **Asia EDGE Competitive Procurement Dialogue Workshop**

HNEI contributed to stakeholder capacity building in this three-day USAID sponsored workshop held in Bangkok on November 18-20, 2019. HNEI GridSTART supported workshop exercise facilitation and presented its experience on RE Grid Integration Challenges and Solutions and a Hawai'i case study on RE Procurement in a High RE Penetration Grid. In response to a request from a Workshop participant, the Indonesia Ministry of Energy and Mineral Resources, HNEI GridSTART delivered in Jakarta on February 10, 2020, a capacity building informational briefing on Renewable Energy Procurements in a High Penetration Grid, employing the Hawai'i experience as a case study for island systems in Indonesia.

### **Laos Solar Pilot Auction**

Under the cooperation framework agreement on August 8, 2017, the Lao Ministry of Energy and Mines (MEM) and USAID Clean Power Asia

(USAID CPA) agreed to work closely on the implementation of planned activities and analysis that will contribute to Lao PDR's exploration of grid-connected solar photovoltaic (PV) and other renewable energy resources, including the design and implementation of a Solar Pilot Auction (SPA) to secure PV projects from Independent Power Producers (IPP). HNEI GridSTART is actively supporting USAID CPA's development of this competitive procurement of PV systems in Laos, utilizing its experience and knowledge of practices for procuring and interconnecting solar projects in Hawai'i and analysis of the transmission and distribution system infrastructure and operations in Laos, delivering technical interconnection requirements and power purchase agreement terms embedded in the SPA request for proposal.

#### **Technical Interconnection and Operating Requirements for Wind and Solar Projects in Laos**

GridSTART has developed technical interconnection and performance requirements and grid codes for wind and solar projects in Hawai'i and Laos. The technical requirements have a direct impact on the counter-party risk allocation in a power purchase agreement (PPA), and thus the commercial and financial terms of the PPA. As such, the application of technical requirements that may utilize the inherent capabilities of today's wind and solar power conversion technologies to their fullest extent must be appropriately balanced with the "bankability" concerns of financing parties. HNEI GridSTART understands, has advised on, and delivered project technical requirements that strike a reasonable balance between project structure and finance interests with project technical requirements desired by the host utility.

#### **MOU between HNEI and Chulalongkorn University, Faculty of Engineering, Smart Grid Research Unit (Chula)**

The MOU establishes a framework for multi-year collaboration on a range of activities exploring approaches, methodologies, tools, techniques, systems, and policies that lead to enhanced resilience and reliability of energy while enabling a clean energy transition through grid modernization and the advancement of smart grid initiatives. Areas of cooperation include:

- Operationalization of a solar PV forecasting system for Thailand generating updated solar PV forecasts every fifteen minutes looking six hours ahead, and two-day ahead forecasts daily;
- A field deployment of HNEI's Advanced Real-time Grid Energy Monitor System (Appendix B4), for integration with other smart grid technologies in Chula's Smart Campus Project in Bangkok, Thailand; and
- Collaborative research with Chula, Hitachi Limited, and Mitsubishi Motors Thailand to deploy two Hitachi advanced bi-directional EV chargers on the Chula campus and develop co-optimized vehicle charge/discharge controls.

#### **Provincial Electricity Authority of Thailand (PEA) Collaboration**

HNEI is developing a capacity building program focused on renewable energy integration and smart grid technologies development and application for PEA engineers. The training leverages the planned installation of several HNEI distributed power monitoring/control units (ARGEMS) on select service transformers in PEA's service territory, engaging the PEA engineers in "mini-projects" associated with the development of new sensing and/or controls applications on the field deployed ARGEMS units and EV bi-directional chargers installed on the Chula campus. As a result of the innovative research conducted in one of the mini-projects, an article entitled "[A Review of Health Assessment Techniques for Distribution Transformers in Smart Distribution Grids](#)" was recently published in the *Applied Sciences* journal.

*Funding Source:* Office of Naval Research

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*Last Updated:* November 2020



# Hawai'i Natural Energy Institute Research Highlights

## Appendix I: International

### I2: EGAT Renewable Integration Study

**OBJECTIVE AND SIGNIFICANCE:** Under the APRESA Award from the Office of Naval Research (Appendix I1), the HNEI's GridSTART is collaborating with the Electricity Generating Authority of Thailand (EGAT), the utility responsible for generation and transmission of power throughout Thailand, to conduct a renewable energy (RE) integration study for the country and enhance the professional capacity of its engineers in advanced study methods and tools.

**BACKGROUND:** The collaboration is pursuant to a Memorandum of Understanding (MOU) executed by HNEI and EGAT (Figure 1) that is focused on a range of research, development, and capability enhancements of mutual interest and benefit.



Figure 1. HNEI-EGAT MOU signing ceremony held on February 28, 2018 at EGAT's corporate headquarters in Bangkok, Thailand.

Activities include constructing a high-fidelity production cost model of the Thai power grid and assessing the operational and economic impact of high penetration solar photovoltaic (PV) scenarios over a five to ten year planning horizon. Applying the calibrated model, HNEI and EGAT are conducting joint analysis with reciprocal visits to Thailand and Hawai'i, empowering EGAT engineers to perform such analyses on its own going forward.

High levels of RE pose grid challenges due to its intermittency and variability and the limited flexibility of legacy power systems to respond to balance system net load. With high levels of RE, conventional generation may need to ramp more quickly over a wider-range to counter the variability and uncertainty of the RE resource production. The cost of dispatched generation may also increase due to less efficient operation and the need for increased operating reserves. Symptoms of increased frequency and voltage variability may appear when reliable grid

operation is at risk, with possible degradation in power quality. While Thailand's moderate level of PV and wind resources today do not yet pose serious operating concerns, Thai energy policy is supporting rapid near-term market growth in RE additions. EGAT's swift action to build the tools and capacity to evaluate high penetration RE scenarios is a necessity.

**PROJECT STATUS/RESULTS:** The HNEI GridSTART team and EGAT built and calibrated a high-fidelity production cost model of the Thai power grid in PLEXOS. In May 2019, HNEI held a multi-day workshop in Bangkok focused on model build, tuning and calibration, and presented model validation results.

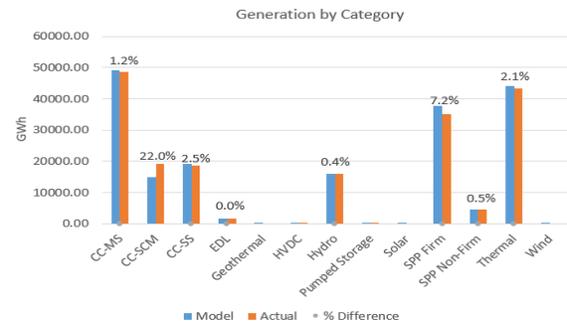


Figure 2. Model validation results.

Time series PV and wind data sets for all existing RE and future high penetration RE cases were developed. Analysis of base, low, medium, and high distributed PV scenarios are underway with conditions of operational concern identified, including excess energy production potential during low load periods. Modeling continues to assess flexibility countermeasures to grid impacts of high RE.

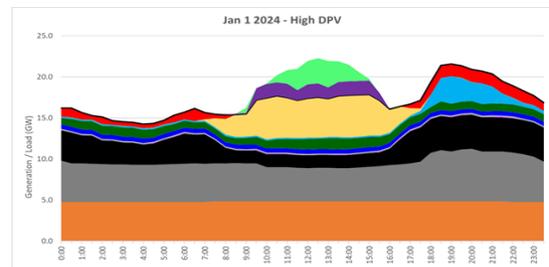


Figure 3. Thailand 2024 min system load day with high distributed PV. Distributed PV shown in yellow and excess PV production in green.

*Funding Source:* Office of Naval Research

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*Last Updated:* October 2020



### I3: Vietnam: Mapping of Renewable Energy Sector Innovation System

**OBJECTIVE AND SIGNIFICANCE:** Under funding of its Asia Pacific Regional Energy System Assessment (APRESA) program (Appendix I1), HNEI is providing financial support and guidance, to the National Institute for Science and Technology Policy and Strategy Studies (NISTPASS) to map the innovation system in the renewable energy (RE) sector in Vietnam. While the development of renewable energy resources in Vietnam is a government priority, there is lack of clarity in regard to the role of many organizations in Vietnam impacting energy development and the relationship between them. One of the objectives of this work is to identify key stakeholders in the RE sector for further policy and institutional support.

**BACKGROUND:** With rapidly growing industrialization and modernization of the economy, energy demand in Vietnam has increased rapidly between 2016-2020 and is predicted to increase by eight percent per annum through 2030 resulting in a four-fold increase in total electricity demand compared to 2014. Under Vietnam's Revised National Power Development Master Plan for the 2011-2020 period, the share of RE is anticipated to significantly accelerate beyond the 10 percent goal previously set for 2030. To meet the aggressive government goals associated with RE innovation, the

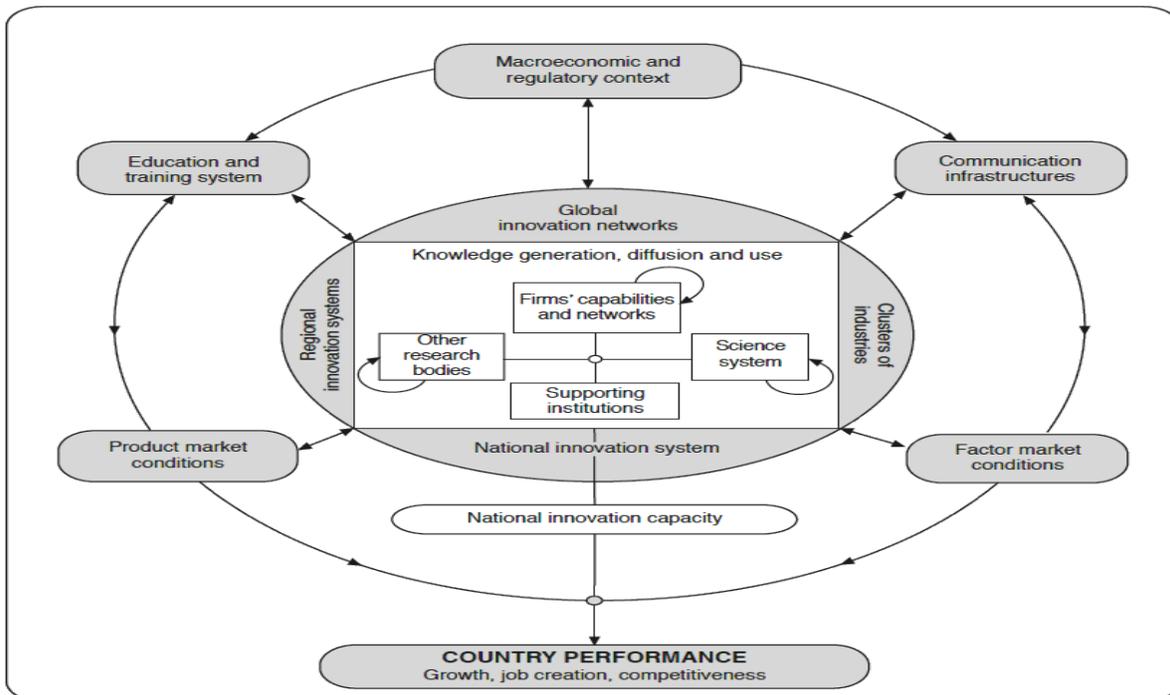
project is focused on identifying relevant organizations in the sector and understanding how they interact with each other and as a system. The analysis will involve an exhaustive review of energy producers, energy consumers, business systems, educational and research systems, policies, regulations and statutes, and infrastructure developers. The project began in August of 2019 and is scheduled for completion in December of 2021.

**PROJECT STATUS/RESULTS:** By May of 2020, NISTPASS completed its initial assessment of the innovation and RE sector innovation system (SIS) in Vietnam. This mapping, based on the National Systems of Innovation Concept in the figure below (OECD, 1999), included the functions and challenges of the SIS, stakeholders and linkages and mutual learning between stakeholders, and preliminary concepts on policy to promote the SIS. The next step is to identify what government support is currently available for energy innovation and where support is most needed to promote future energy innovation growth in Vietnam.

*Funding Source:* Office of Naval Research

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*Last Updated:* November 2020





**OBJECTIVE AND SIGNIFICANCE:** Under this U.S. Trade and Development Agency (USTDA) project, HNEI was selected by prime contractor GE Energy Consulting, to offer recommendations on grid scale Battery Energy Storage Systems (BESS) for consideration by Vietnamese regulators for the advancement of policy and tariff formulation at the national level. HNEI’s policy recommendations incorporated specific use cases that apply to Vietnam Electricity National Load Dispatch Center’s (EVN NLDC) transmission grid in Vietnam, taking into consideration grid related issues evaluated in GE’s analysis. The ensuing policy recommendations are intended to support BESS as a vital complement or addition to new power generation and power transmission infrastructure required to meet Vietnam’s the unique grid challenges.

**BACKGROUND:** HNEI evaluated BESS use cases in California and Hawai‘i deemed illustrative for EVN NLDC based on general similarities of grid issues, generation issues, and load issues observed in the selected regions and Vietnam. Integrated in HNEI’s evaluation are relevant analyses, regulatory and policy works of the California Public Utilities Commission, the California Energy Commission, and the National Renewable Energy Laboratory on BESS and renewable generation. The intent of this evaluation is to identify specific BESS use cases to be adapted and recommended for EVN NLDC and Vietnam, based on similarities of grid issues, generation issues, and load issues observed in the selected regions and Vietnam.

**PROJECT STATUS/RESULTS:** The following mechanisms were among those recommended for urgent action given Vietnam’s rapidly growing economy and energy demand:

- Direct investment in demonstrations;
- Mandatory targets;
- Regulatory and agency analyses and roadmaps;
- Procurement rules and procedures; and
- Utility programs supporting energy storage.

Hawai‘i and California case studies highlighted the importance of understanding the limitations of transmission and distribution systems when planning the addition of renewable energy resources. For BESS applications and potential value streams, arbitrage alone cannot pay for storage, and a battery providing transmission congestion relief may also provide value streams such as firm capacity, voltage regulation, frequency regulation, spinning reserves or arbitrage to some extent. Since providing one value stream can impact the ability to deliver another, trade-offs between value streams need to be assessed carefully. In other words, value stacking may be the only way to get cost-effective benefit from storage.

*Funding Source:* U.S. Trade and Development Agency via subaward from GE Energy Consulting

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*Last Updated:* November 2020

Policy Recommendations – Urgent Action	
<b>KEY MESSAGES</b>	
Apply Value Stacking to Achieve Cost-Effective Benefit from Storage	
Consider Appropriate Sizing & Location of BESS Near Solar Installations to Optimize Technical Benefits & Economics	
Top 5 BESS Demonstration Sites Offers Proof of Concept Prior to Scaling Up	
Grid Services via BESS (i.e., Provision of Operating Reserves Voltage Support, and Peak Shifting) Offers Additional Revenue	
<b>REGULATORY POLICY</b>	
Direct Investment in Demonstrations	
Mandatory Targets	
Guidance vis-à-vis Regulatory & Agency Analyses & Roadmaps	
Guidance vis-à-vis Procurement Rules & Procedures	
Utility Programs and Promotions in Support of Energy Storage	
<b>FINANCIAL METHODOLOGY AND INCENTIVES</b>	
Build-Own-Operate-Transfer (BOOT) Model May be Best Near-Term Financing Option	
Improve Market Certainty & Reduce Risk by Accelerating Market Reforms Plus Investment Tax Credits & RPS	



**OBJECTIVE:** The goal of this project is to demonstrate an advanced control system for an artificial intelligence (AI)-based microgrid incorporating distributed solar and energy storage will optimize energy management, reduce costs, and improve resilience of the seawater distribution system at the Hawai'i Ocean Energy, Science & Technology (HOST) Park. The microgrid control system has been designed with the capability to provide comprehensive energy management of the entire 900-acre HOST Park where more than 40 companies operate business/pilot sites.

**BACKGROUND:** HOST Park is a unique outdoor demonstration site for renewable energy, aquaculture and other ocean-based sustainable technologies. The Park includes three sets of pipelines capable of delivering up to 100,000 gallons per minute of cold seawater from depths of 3,000 ft. The innovative green economic development park is administered by The Natural Energy Laboratory of Hawai'i (NELHA), an agency of the State of Hawai'i. Interruptions in electrical service have the potential to irreparably damage the businesses that depend on the seawater for their agricultural and production requirements. The proposed microgrid, with AI capability, is intended to reduce utility costs and reduce or eliminate outages of the seawater pumping system.

The Hawai'i Natural Energy Institute (HNEI) conceived the project, initiated efforts to apply for

Korea Institute of Energy Technology, Evaluation and Planning (KETEP) grant funding, and helped form the consortium of United States and Korean participants. In 2018, KETEP awarded the project team a grant of KrW 1,940 million, approximately USD 1.73 million via the Korea Ministry of Trade, Industry, and Energy as part of their International Energy Collaborative Research and Development Program. The project entails a detailed design, deployment, testing and evaluation of a AI microgrid that includes photovoltaic (PV) panels and battery energy storage systems (BESS) at the HOST Park.

**PROJECT STATUS/RESULTS:** HNEI supports the microgrid development project by advising on requirements for grid interconnection between the proposed HOST Park microgrid and the HELCO grid, including the potential applicability and impacts of microgrid service tariffs; functional requirements and use cases for the microgrid; and project team engagement with the engineering, procurement and construction (EPC) and financial contractors. Ground breaking is expected to take place in December of 2020 with the microgrid to be operational by the project end-date of October 31, 2021.

*Funding Source:* KETEP (subcontract with Encored, Inc.)

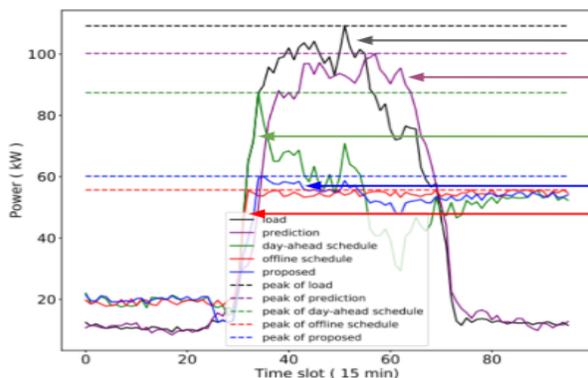
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*Last updated:* October 2020

### Microgrid Operation

#### On-grid operation

#### Short-term compensation for failure of forecasting



- Problem
  - The error of forecasting for load and PV generation deteriorates profit from a day-ahead optimal solution for ESS
- Solution
  - Machine-learning & compensating from previous experiences what the relation between the error and optimal solution in higher data resolution
  - *Practical Operation Strategies for Energy Storage System under Uncertainty*, 2019, Energies

## **ADDITIONAL PROJECT RELATED LINKS**

### **PAPERS AND PROCEEDINGS:**

1. 2020, R-K. Kim, M.B. Glick, K.R. Olson, Y-S. Kim, [MILP-PSO Combined Optimization Algorithm for an Islanded Microgrid Scheduling with Detailed Battery ESS Efficiency Model and Policy Considerations](#), Energies, Vol. 13, Issue 8, Paper 1898. (Open Access: [PDF](#))
2. 2019, J-W. Chang, G-S. Lee, H-J. Moon, M.B. Glick, S-I. Moon, [Coordinated Frequency and State-of-Charge Control with Multi-Battery Energy Storage Systems and Diesel Generators in an Isolated Microgrid](#), Energies, Vol. 12, Issue 9, Paper 1614. (Open Access: [PDF](#))

### **PRESENTATIONS:**

1. 2019, M.B. Glick, [Smart Grid and Microgrid for Archipelagic Communities - Power Play of Policy-Industry-Capacity-Infrastructure](#), Presented at the 5<sup>th</sup> ASEAN Smart Grid Congress, Johor, Malaysia, December 4.
2. 2019, M.B. Glick, [Hawai'i's Island Energy Transition - A Policy-Driven Approach & Framework](#), Presented at the Alaska Wind-Diesel Workshop, Anchorage, Alaska, June 24.
3. 2019, M.B. Glick, [Microgrid Law & Policy of Hawai'i - Strategies for Resilience and Cost Control](#), Presented at the International Conference on Microgrid Law & Policy in Asia-Pacific Islands, Seoul, South Korea, May 13.
4. 2019, M.B. Glick, [Energy Policy of the State of Hawai'i – Update on the World's Leading Energy Transition Model](#), Presented at the 6th Annual International Electric Vehicle Expo/4th Annual International Energy Conference & Korea EV Development Forum, Jeju, South Korea, May 9.



**OBJECTIVE AND SIGNIFICANCE:** The project objective is to foster international collaboration around smart grids, particularly distribution systems and microgrids with solar photovoltaics (PV) and energy storage. The Hawai'i Natural Energy Institute (HNEI) at the University of Hawai'i is among an esteemed group of U.S. institutions including Washington State University (WSU), Massachusetts Institute of Technology (MIT), Texas A&M University, General Electric, ABB, and several U.S. Department of Energy national laboratories, as well as peer organizations in India including five Indian Institute of Technology (IIT) campuses. This project is an important opportunity to highlight Hawai'i's challenges and solutions at the forefront of renewable energy integration, while inviting input from international leaders in smart grid research and technology development.

**BACKGROUND:** HNEI's work, conducted by its GridSTART team addresses the following objectives within the larger project:

- To provide models and data from distribution circuits with high distributed PV penetration as a basis to explore advanced devices, controls, and distribution system operation (See Figure 1);
- To operate these models on HNEI's hardware-in-the-loop (HIL) equipment linked in real time to devices and controls at, for instance, WSU and the National Renewable Energy Laboratory (NREL) as a means to provide realistic testing in a controlled environment;
- To provide live updates of multi-horizon PV forecasts (Appendix B5) from HNEI's solar forecasting system alongside real PV measurements to support third-party applications including distribution grid operations and optimal energy storage control; and
- To provide outreach and workforce development addressing smart grid technologies and applications and grid integration of renewable energy.

**PROJECT STATUS/RESULTS:** As of year three of the six year project, UH researchers and postdoctoral fellows have:

- Adapted Hawai'i distribution circuit models for real-time simulation (Figure 1);
- Provided ongoing satellite-based PV forecasts;

- Co-authored two papers and an extended abstract;
- Hosted two professors from IIT for a U.S.-India Partnership to Advance Clean Energy (PACE) fellowship;
- Presented webinars and prepared an exhibit attended by approximately 1,000 Hawai'i K-12 students (Figure 2); and
- Advised two high school students on research projects related to the variability of PV generation.

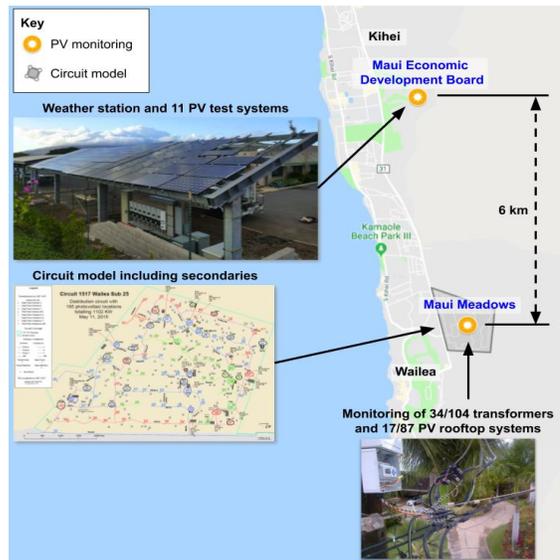


Figure 1. Overview of HNEI's data and models from the area of South Kīhei, Maui.



Figure 2. Poster and interactive display presented to K-12 students at the 2019 SOEST Open House at UH Mānoa.

**Funding Source:** U.S. Department of Energy (subaward from Washington State University); Energy Systems Development Special Fund

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**Last Updated:** November 2020