David Lassner
President

DEPT. COMM. NO. 167

UNIVERSITY of HAWAI'I

December 20, 2021

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: https://www.hawaii.edu/offices/government-relations/2022-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.

Sincerely,

David Lassner
President

Enclosure

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Honolulu, Hawai'i 96822
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UNIVERSITY OF HAWAIʻI SYSTEM ANNUAL REPORT

REPORT TO THE 2022 LEGISLATURE

Annual Report from the
Hawaiʻi Natural Energy Institute

HRS 304A-1891

December 2021

Hawaiʻi Natural Energy Institute

School of Ocean and Earth Science and Technology
University of Hawaiʻi at Mānoa
Annual Report to the 2022 Legislature
HRS 304A-1891

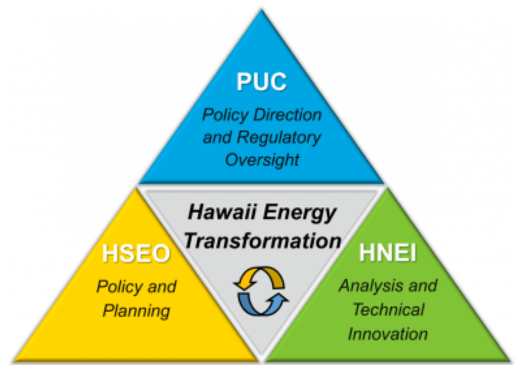
Annual Report on Activities, Expenditures, Contracts Developed, Advances in Technologies, Work in Coordination with State Agencies and Programs, and Recommendations for Proposed Legislation, required in accordance with HRS 304A-1891 (Act 253, SLH 2007).

1. INTRODUCTION

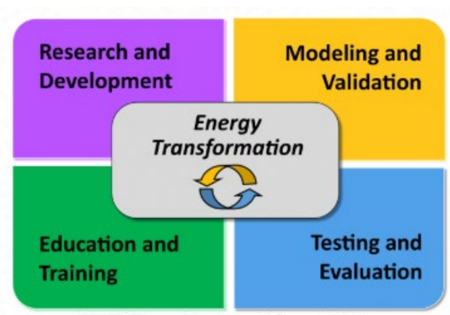
The Hawaiʻi Natural Energy Institute (HNEI) was created in 1974 to facilitate the development of the state's natural energy resources and reduce fossil fuel use in Hawaiʻi. Early efforts included resource assessments, demonstration projects, and research and development in the areas of alternative fuels, 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 Hawaiʻi's energy mix. HNEI emerged as a leader for sustainable energy development and the deployment and demonstration of emerging energy technologies.

In 2007, the Hawaiʻi 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 Hawaiʻi 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.



HNEI Functions and Capabilities

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 Hawaiʻi 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 Hawaiʻi at Mānoa (UH), HNEI receives state funding via Hawaiʻi General Fund through the university budget that is sufficient to support its Director (Richard Rocheleau), three administrative support staff and partial salaries (60% to 80%) of its tenure or tenure-track faculty (permanent faculty). In 2021, HNEI's permanent faculty comprised 6 members. Permission to advertise for a seventh has been approved. 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), Naval Facilities Engineering Command, and the U.S. Department of Energy, 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. HNEI's extramural awards also generate indirect funds "Research and Training Revolving Funds" of which approximately 25% is returned to HNEI to facilitate operations and research. In addition to addressing national and international needs, many of the projects funded by the entities identified above directly or indirectly support Hawaiʻi's clean energy goals.

In addition to supporting the balance of HNEI's permanent faculty, the extramural funds from these sources support temporary faculty and staff including engineers, scientists, and support personnel as well as post-doctoral fellows, students, and visiting scientists within HNEI. Due to the multidisciplinary nature of HNEI's work, these extramural funds also support faculty, students, and post-doctoral fellows in other departments and colleges.

As part of its responsibilities under ACT 253, 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 Hawaiʻi's dependence on fossil fuels; and to conduct analysis (often in support of the PUC) that directly supports Hawaiʻi'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 in Appendix A and Appendix B, HNEI projects do inform legislators and other Hawaiʻi 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 is a longtime member and supporter of the Hawaiʻi Energy Policy Forum (HEPF), a collaborative energy planning and policy group comprising approximately 40 representatives from business, academia, government, and non-profit organization. In 2021, HNEI assumed responsibility for coordination of the HEPF activities.

Staffing and expenditures for 2021 are summarized in the two tables below.

STAFFING Director: Richard E. Rocheleau

Permanent Faculty (FTE)	6
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 $ 1,411,775
Tuition and Fees S Funds $ 39,439
Research and Training Revolving $ 414,986
Extramural Awards $ 8,980,166
Energy Systems Development Special Fund $ 461,466

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 60 discrete projects. The various activities and key accomplishments under each of these projects are summarized in a series of summaries included within the nine Appendices of this report. These Research Highlights provide a 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). 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 Hawaiian 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 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 addressing and solving 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. During the current reporting period, HNEI and its primary partner in these efforts, Telos Energy, conducted a variety of analyses, using advanced probabilistic tools developed in the previous year, to assess system reliability and to better understand the impacts of these significant changes to grid operations in Hawai‘i. The importance of this work was made more critical by the pending retirement of the AES coal plant and recent potential delays in implementation of the planned PV + storage projects. The analysis has shown that, even at these proposed high levels of solar penetration, solar+storage provides excellent capacity reliability. The results of this work are being used by HECO and the HPUC in their decision making.

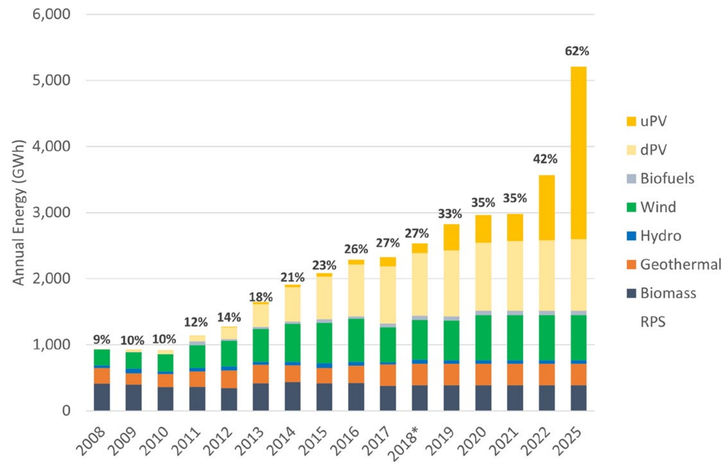


Figure 1

These technical analyses, to date conducted for the island of O‘ahu and Maui are described in more detail in Appendices A4 and A7. In 2021, HNEI also evaluated potential benefits of converting the AES coal plant to operation on biomass (Appendix A5) and conducted an evaluation of the level of control required to maximize the grid benefits from additional distributed solar on O‘ahu (Appendix A6).

In addition to the technical analysis summarized above, 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 (Appendices A1 through A3). These activities include supporting analyses for the PUC, support of the HECO’s Integrated Grid Planning efforts. Also new in 2021, HNEI assumed responsibility for management of the Hawai‘i Energy Policy Forum based at the UH Mānoa Campus. Finally, in Appendix A are short summaries of HNEI’s work to assist the Department of Health to develop policies for the future disposal of electronic waste including PV and batteries (Appendix A8); and a new microgrid project funded by U.S. Department of Energy (Appendix A9).

<u>Appendix B: Grid Technology Development</u>

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 can serve as ideal test beds for energy solutions for the nation. 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. Funding for these projects includes the Office of Naval Research and the U.S. Department of Energy, with projects of high relevance to Hawai‘i leveraged with funding from the barrel tax.

Appendices B1 through B4 summarize three technology development efforts including development of patent pending instrumentation for real time grid control; technology for solar forecasting across multiple time scales; and two microgrid studies, one to demonstrate a high efficiency DC microgrid at Coconut Island and a study of the benefit of developing a microgrid at NELHA. Appendices B5 and B6 describe efforts to improve energy efficiency and resilience at two U.S. Department of Defense facilities. Appendix B7 summarizes efforts to demonstrate the value of distributed virtual power plant comprised of smaller PV + storage elements.

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 and an essential component for reducing Hawai‘i’s greenhouse gas footprint. HNEI conducts research, testing, and evaluation that supports the development of alternative fuels including biomass and biofuels, hydrogen, and solar fuels. 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 while Appendix C2 summarizes the potential for renewable gas production in Hawai‘i. Appendices C3 through C6 describe technology development efforts for the production and characterization of alternative fuels and other high value products.

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(autonomous) aerial and undersea vehicles, and for grid services. These activities, ranging from laboratory research to evaluation of grid deployed battery energy storage systems are described in the attached Appendices. Appendix D1 summarizes HNEI's ongoing partnership with the Naval Research Laboratory to develop reliable fuel cell power systems for unmanned aerial vehicles. Appendices D2 through D5 describe multiple approaches for development of more efficient, lower cost catalysts for fuel cells. HNEI's work in understanding the reliability and lifetime of Li-ion batteries at scales ranging from single cells to grid deployed systems is described in Appendices D6 though D8. Appendices D9 and D10 describe nascent programs to develop new, lower cost battery technologies.

Appendix E: Advanced Materials

The six projects included in the Advanced Materials group, include development of novel techniques for the production of low cost photovoltaics (Appendix E1), the production of high value products from biomass (Appendix E2), multiple programs focused on the development of low cost, high performance hydrogen storage technologies (Appendices E3 through E5), and a new project to develop novel solutions for forward osmosis seawater desalination (Appendix E6).

Appendix F: Energy Efficiency

The four projects included in the HNEI energy efficiency portfolio were selected for their near-term value to Hawaiʻi. Appendix F1 describes environmental monitoring at the site of the, then proposed, outflow location for Honolulu Seawater Air Conditioning project. While the Honolulu SWAC is no longer being considered, this work can help inform future SWAC development. The remaining three projects are related to building efficiency. Appendix F2 summarizes a project intended to facilitate improved building efficiency in Hawaiʻi's transit-oriented development areas. Appendices F4 describes a project that addresses development of advanced lighting controls for improved efficiency and security. Appendix F5 describes a short term project funded by the City and County of Honolulu intended to provide an immediate pathway for relief to businesses from the coronavirus pandemic by using virtual energy audits to quickly identify operational energy savings from potential energy efficiency measures (EEMs) and indoor air quality improvements.

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 Hawaiʻi Authority (NELHA), the County of Hawaiʻi, and the Hawaiʻi Island Mass Transit Agency (Hele-on bus). As of the date of this report, the facility is operational and buses are being prepared for shipment from Oʻahu to the Big Island. Appendix G2 describes a demonstration of two-way EV charging intended to develop advanced controls optimizing grid services and vehicle use. This system recently became operational with results expected in early 2022.

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 Hawaiʻi. This site, still the premier open water test site in the U.S., continues to be an invaluable resource for developers needed to test prototype systems in a real world environment. 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. The proposed 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. In 2021, HNEI's international efforts grew considerably. Appendix I1 provides brief summaries of a number of projects under this award, including ones in Vietnam, Thailand, Indonesia, Cambodia, and the Philippines. In 2021, HNEI's Grid***START*** team provided technical assistance and training to a range of entities in this region. Appendices I2 through I14 provide additional detail on a wide range of projects, including ones funded by the APRESA award as well as several new projects in which HNEI serves as a subawardee to the prime contractor in large USAID funded projects.

APPENDICES

Appendix A: Hawaiʻi Energy Policy and Analysis

Appendix B: Grid Technology Development

Appendix C: Alternative Fuels

Appendix D: Electrochemical Power Systems

A1: Decision Support Services to the Hawaiʻi Public Utility Commission

BACKGROUND: The Hawaiʻi Public Utility Commission (PUC) is the regulatory body tasked with reviewing and deciding on investment decisions, rates, and long-term planning of Hawaiʻi'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.

A number of issues related to the integration of renewable energy technologies are discussed in more detail in other project summaries located in Appendix A. 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 briefly discusses four recent examples of HNEI support to the PUC support:

- Lifecycle analysis of greenhouse gases for Hawaiʻi relevant generating technologies;
- Review of proposed conversion of AES power plant to biomass;
- Analysis of Kapolei storage project economics; and
- Analysis of the emergency DR program

PROJECT STATUS/RESULTS:

Lifecycle Greenhouse Gas (GHG) Analysis: Hawaiʻi has been in the forefront of integrating renewable energy technologies into its energy mix. In 2008, the state launched the Hawaiʻi Clean Energy Initiative (HCEI) with the goal to substantially reduce the use of fossil fuels. Since then, there have been a number of modifications leading to the current RPS goal of 100% fossil free energy use by 2045.

Recently, life-cycle analyses (LCAs) for GHG emissions in Hawaiʻi 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 Hawaiʻi relevant energy technologies and resources to provide the PUC with a 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 conducted further evaluation of those applicable for Hawaiʻi.

While some renewable energy generation technologies do not emit CO_2 at the point of use, there may be embedded emissions that are created during the full life cycle of the technology. A full accounting of emissions requires that emissions that arise from these other steps, such as production (mining and manufacturing), operation and maintenance, and disposal/reuse, be included. In other words, the life-cycle of all energy technology will have some GHG emissions, even if the actual production of electricity does not produce any GHGs. Based on the literature and additional analysis conducted by HNEI, the range of estimates for lifecycle emissions was found to be wider than expected. Even for well-defined technologies, such as PV, substantial ranges were found, partly due to variations in the technology but largely due to variations 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 comprehensive site-specific studies. For biomass and biodiesel combustion, large amounts of CO_2 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, some publications offer contradictory conclusions regarding biomass emissions and their timing. HNEI is evaluating these analyses and will incorporate the findings in this deliverable to the PUC.

Following the development of the draft deliverable, HNEI will convene a meeting of stakeholders from Hawaiʻi and experts from the U.S. Department of Energy's (DOE) national laboratory system. HNEI expects to convene this expert panel in early 2022 with a final report to the PUC by June 2022.

Review of AES Proposal to Convert Coal Facility to a Biomass Combustor: The AES coal-fired power plant is scheduled to be closed in September 2022. Recently, the Hawaiʻi State Energy Office asked AES about the possibility to convert this facility to a biomass combustion unit. HNEI conducted an initial analysis into the feasibility of such a conversion.

The resulting analysis showed that this conversion warranted a more comprehensive review. The advantages included:

- Utilizing the existing transmission system;
- Increasing the renewable portfolio percentage by an additional 20%;
- Effective use of existing industrial lands;
- Providing firm renewable power to the grid; and
- Replacing oil-fired without impacting future solar development.

The cost of electricity from this facility relative to that of displaced oil is dependent on the cost of oil and warrants a closer examination over the expected life of the plant.

In 2021 addition to briefing PUC staff, HNEI briefed the PUC, the utility, and members of the Senate Ways and Means and the Energy and Commerce Committees on these results.

Kapolei BESS Analysis: HNEI conducted an analysis of the efficacy of the Kapolei system. The preliminary findings indicated that direct fuel savings were not enough to compensate for Kapolei's annual PPA price of $24 million, even in a conservative scenario where Stage 1 & 2 solar + BESS projects provided no grid services.

However, other factors were identified that could increase both net savings and overall value of the Kapolei system. These included near capacity to help ensure system reliability in the case of delays of the proposed Stage 1 and Stage 2 projects; and future capacity that could help facilitate additional oil-fired generation retirements and higher reserve margins to allow increased solar and/or wind development.

The HNEI analysis showed that integration of Stage 1 and Stage 2 hybrid solar-storage plants and retirement of AES results in very little curtailment limiting the energy arbitrage benefits of the Kapolei BESS. However, inclusion of Kapolei was found to reduce oil consumption regardless of what resources charge the battery (renewable or fossil), even after accounting for round-trip energy losses. Addition of Kapolei BESS to the Oʻahu energy mix was also found to reduce cycling of the PV-connected storage offering potential opportunities for additional grid-connected or rooftop solar with or without storage.

Distributed Energy Resources (DER) and Demand Response (DR) as Replacement Capacity for AES Coal-Fired Power Plant: HNEI examined the use of DER and DR as capacity replacements following the retirement of the AES coal-fired power plant. Of particular concern was the need to evaluate the closure, planned for September 1, 2022, during months of peak load (August - October) immediately following the plant closure.

At current levels of solar and wind penetration; standalone storage, DER with storage, and DR were shown to provide capacity equivalent to other firm resources and to grid-scale solar + BESS resources. While the DER and DR can be an important component of the 2022 transition, the need after Stage 1 and Stage 2 are fully deployed has not been well characterized.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2021

A2: Support of Integrated Grid Planning

OBJECTIVE AND SIGNIFICANCE: In 2018, under guidance from the Hawaiʻi Public Utilities Commission (PUC), the Hawaiian Electric Company (HECO) 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 to meet the goals of legislatively mandated Renewable Portfolio Standards. A Technical Advisory Panel (TAP) was established to provide a third-party, technical, and unbiased review of HECO's modeling and analysis efforts to ensure that best tools and methodologies are being used. The TAP consists of experts from around the country including members from National Laboratories, industry groups and other utilities. Based on direction from PUC Order No. 36725, *Providing Guidance on the IGP*, HNEI chaired the IGP's TAP from its inception in 2018 to October 2021.

KEY RESULTS: HNEI's involvement in the IGP and its leadership role in the TAP has helped ensure that HECO is moving forward in addressing grid issues related to increasing amounts of renewable energy, which includes both distributed behind-the-meter (BTM) generation, utility-scale generation, and utility-scale and BTM storage. The TAP provides HECO with independent and technical oversight from outside experts, helping ensure that the utility is using industry-accepted methods, inputs, and assumptions.

Key activities of the TAP have focused on assisting HECO in revising their approaches to analysis. These have included advice in regard to the suite of tools and process for integration of those tools and methodologies. HNEI and its subcontractor Telos Energy developed a modeling framework (Figure 1) that was adopted as the IGP modeling framework by HECO. In addition, HNEI provided recommendations insight to using "bookends" to delineate the potential impacts of load uncertainty. During 2021, significant effort was expended by HNEI to quantify alternative methodologies and metrics from using energy reserve margins (ERM) in determining resource adequacy. These probabilistic tools are also being used in the analysis of grid reliability with the pending AES coal plant retirement.

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.

Following an initial period in which the progress of the IGP did not fully meet expectations, HNEI was, in 2020, requested to assume an expanded role in supporting the IGP initiative. This increased support included re-constituting the TAP membership, working with HECO staff to revise their approach for

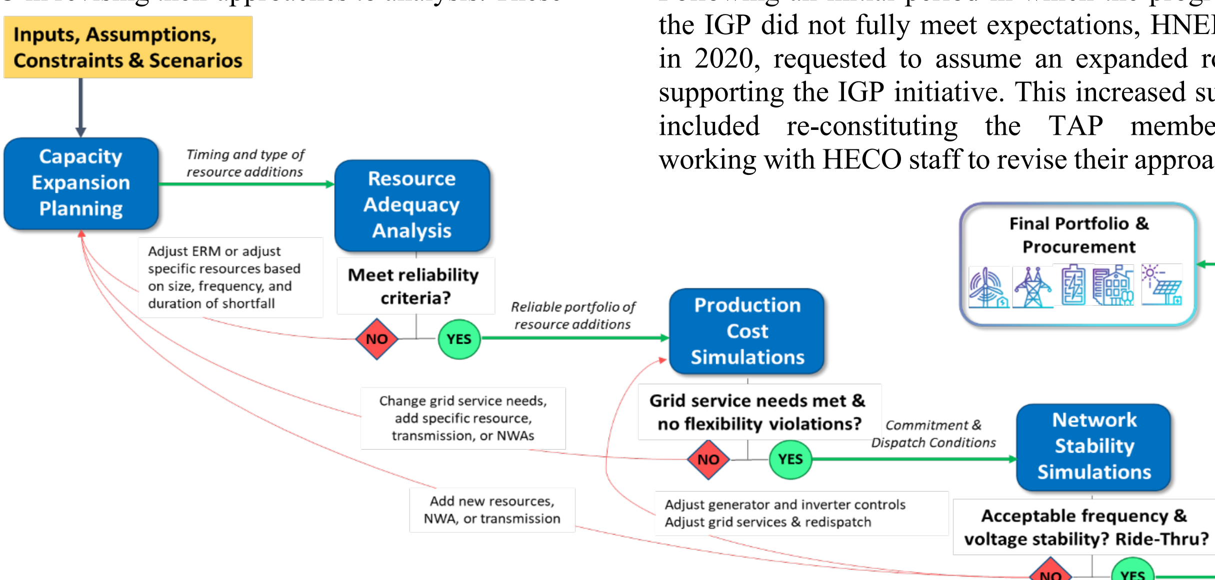


Figure 1. HNEI Modeling Framework Adopted by the IGP.

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, HNEI took an expanded role in participating in all of these activities.

This approach was 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 and confirmed in a May 2020 letter from HECO to the PUC.

Through its November 2020 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 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. HNEI's chairmanship of the TAP operated under these new principles through October 2021 when a new Chair was selected. HNEI continues to play a very active role in all aspects of the IGP process and TAP.

PROJECT STATUS/RESULTS: HNEI's role as the TAP Chair was an ongoing process that included regular discussions with the HECO planning team, meetings with the TAP members, and active engagement in HECO's technical working groups. HNEI continued to be involved in assisting HECO in properly formulating questions and agendas for TAP meetings in order to make these meetings productive and effective.

As part of this process, HNEI also helped to create consolidated reporting to better share IGP results with TAP members who may not be aware of Hawai'i-specific events, trends, or challenges. Despite no longer chairing TAP, HNEI and their contractor Telos Energy continue to be actively engaged in other parts of the IGP stakeholder process, including active involvement in the Stakeholder Committee, the Stakeholder Technical Working Group, and other relevant Technical Working Groups.

In order to assist HECO in providing more clarity in their internal analyses, HNEI proposed that HECO develop "bookend" scenarios. That is, rather than run a large number of scenarios with variable forecasts and assumptions, it was recommended that HECO use a limited set of scenarios to analyze the impact of extreme or "bookend" values for the forecast loads. The intent was to reduce modeling and analysis time spent developing detailed layers of forecasted energy usage where it was difficult to discern the impact of changing various variables where the intent was to use modeling outputs to better understand critical factors that impacted the future grid, that have a better focus on specific information. In this manner, one could determine the impact of aggregated impacts on grid operations to ensure reliable grid operations over the wide range of forecasts.

HNEI and its contractor, Telos Energy, frequently raised concerns about the excessive use of the capacity expansion model, RESOLVE, in evaluating impacts and implications related to its use in characterizing reliability and grid service needs. HNEI has demonstrated that these types of analyses should be done in tandem with probabilistic analyses that can be used to measure grid reliability from the use of RESOLVE. Grid planning should include both a simplified ERM deterministic metric and more detailed probabilistic metrics for resulting portfolios.

The HNEI team will continue to provide technical and unbiased review and recommendations for HECO's long-term planning and procurement process to ensure that the State can achieve its ambitious renewable energy policy in an efficient and reliable manner.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2021

A3: Hawaiʻi Energy Policy Forum

OBJECTIVE AND SIGNIFICANCE: Through this project, HNEI supports the activities of the Hawaiʻi Energy Policy Forum (HEPF) in its mission to enable informed decisions to advance Hawaiʻi'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 by the University of Hawaiʻi's College of Social Sciences as a collaborative energy planning and policy group consisting of Hawaiʻi's electric utilities, oil and natural gas suppliers, environmental and community groups, renewable energy industry, academia, and federal, state, and local government. In its first five years, the Forum was instrumental in 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 a Legislative Briefing at the Capitol at the opening of each legislative session, an annual Hawaiʻi Clean Energy Day event, and sponsors programs to develop reliable information and educate and raise awareness in the community. Historically, HNEI faculty members have contributed 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 "Hawaiʻi: State of Clean Energy" show.

PROJECT STATUS/RESULTS:

HEPF Restructure in 2021

The combination of key staff departures and impacts to staff and programs from the pandemic, the School of Social Sciences wound down the operations of HEPF during 2021. In the Spring and Summer of 2021, HNEI was approached to take over the operations and management of HEPF and the HNEI Director agreed to transfer HEPF to become a program of HNEI, with the transition starting in September of 2021. Since that time, HNEI has hired two graduate research assistants, established an office, transferred assets from the School of Social Sciences to HNEI, and reached out to existing and new members to establish the programmatic focus and content for 2022 and beyond under the direction of HNEI.

Hawaiʻi Legislative Briefing

Prior to the restructure, the Hawaiʻi State Energy Office and the Hawaiʻi Energy Policy Forum held the 2021 Legislative Energy Briefing on January 15th. The agenda included a wide range of speakers who shared their current situation, challenges, and 2021 solutions to help Hawaiʻi achieve a resilient, prosperous, carbon free economy.

Member-Driven Initiatives, Online Resources and Outreach

Peer Exchanges: Due to COVID-19, HEPF conducted member to member exchanges of best practices virtually from August of 2020 and through the first quarter of 2021, starting with the Department of Land and Natural Resources (DLNR) regarding multi-modal mobility hubs. The State's Climate Change Commission sought and was awarded grant funds from Oʻahu Metropolitan Planning Organization and other sources to develop a plan for assessment of state parking facilities statewide that will allow for multi-modal use.

Online Resources: In the past two years, HEPF updated and created new resources for members and the public focusing on policy in the legislature and the PUC as described below:

- 2020 State legislature bill tracking spreadsheet, documenting the progression of bills and the final scope of bills passed;
- Updated State Act Database to 1999-2020 (from 2002-2018), which includes topic categorization, and links to the Hawaiʻi 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.

Funding Source: Energy Systems Development Special Fund

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Last Updated: November 2021

A4: 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 ongoing study is to evaluate the ability of proposed solar + storage resources to provide the required energy needed while also maintaining grid reliability with the pending AES coal plant retirement. The results of this analysis have been briefed to the Hawai‘i Public Utility Commission (PUC), the utility, and other stakeholders. Ongoing work is presented as part of the Governor's "Powering Past Coal" task force. The results of this work 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 and reported last year, are being used to assess capacity reliability risks associated with the AES retirement, updates for utility plans, and possible impacts due to delays in project schedules. Analysis shows that deployment of the Stage 1 solar + storage systems along with a small fraction of the Stage 2 projects would maintain or even improve risk relative to current operations, but that timing of resource additions is critical. Stand-alone storage, demand response (DR) and behind-the-meter solar with storage (DER) similarly reduces risk.

As a result of delays in Stage 1 deployments, HECO has proposed to restructure their planned outage schedules for the critical months of September - November 2022. The HNEI-Telos Energy analysis shows this to be an effective means to mitigate risk although some amount of additional resources (~40 MW) would still be required to achieve the same capacity reliability as found in current operations. Based on the latest (November 2021) projections for Stage 1 deployments, utility plans for rescheduled maintenance, and the PUC's emergency DR program, current plans appear adequate to transition through the retirement of the coal plant. However, with ever-changing delivery schedules due to both local issues, such as interconnection requirement studies, permitting, and global shipping delays, this work is ongoing and will continue until sufficient resources are deployed to ensure capacity needs are met.

Background: As the Hawai‘i grid transitions to renewables including higher percentages of variable renewable energy, these new resources are required to provide not only energy, but also to provide capacity and other grid services currently provided by fossil generation. Current utility plans call for combining solar with battery storage resources allowing solar energy to be shifted from the middle of the day, when there is surplus renewable generation, to other times of the day including the evening peak-load hours that occur after the sun has set. 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. The first test of this strategy revolves around the pending retirement of the AES coal plant in September 2022.

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. SB 2629 enacted in 2020 bans coal-fired generation in Hawai‘i after 2022, ensuring the AES retirement. The objective of this ongoing study, requested by the PUC, is to evaluate the ability of the planned Stage 1 and Stage 2 utility scale solar + storage plants to provide the capacity resources needed to ensure reliable grid operations once the AES coal plant is retired.

The Stage 1 solar + storage projects were originally proposed to be completed in 2022, prior to or concurrent with the AES retirement. However, as of November 2021, several of these projects are encountering delays, pushing their delivery dates to beyond the legislatively mandated AES coal facility retirement.

Beyond the Stage 1 projects, an additional 274 MW of solar with 1,223 MWh of battery storage plus a 185 MW, 565 MWh stand-alone battery energy storage project to be located in Kapolei was awarded in the Stage 2 RFP. While the Stage 2 projects would provide significant capacity, they are not expected to be online until the end of 2022 or later.

Novel "Stochastic Modeling" methodologies, developed by HNEI and Telos Energy and summarized in HNEI's 2020 report to the legislature, that accurately account for the chronological operations of storage, solar variability, and generator outages are being utilized to determine if the proposed solar + storage systems can maintain reliability when AES is retired. These models are being used to identify key timelines as well as to assess the viability of other mitigating measures such as DER and the proposed rescheduling of HECO generator maintenance.

PROJECT STATUS/RESULTS: The stochastic methodology previously described is being used to evaluate the reliability the O'ahu grid, following the AES coal plant retirement assuming different buildouts of utility-scale solar + storage resources. Each case is analyzed across 1,008 random draws (replications) of chronological dispatch, representing 21 years of solar data and 48 unique outage profiles for each year of solar data. The output of each analysis includes the number (probability), the magnitude, and the duration of capacity shortfall events that might 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 one representing the full buildout of recently awarded Stage 1 and Stage 2 projects (426 MWac of solar with 1,833 MWh of battery storage).

This analysis was conducted with and without the proposed adjusted maintenance schedules to understand the reliability benefits of HECO's proposal to limit planned generator maintenance during the peak reliability risk window from September 2022 through the end of the year.

The matrices in Figure 1 below summarize the number of hours of unserved energy for two representative cases, the Base Case, and a case assuming the AES retirement and full build out of the Stage 1 projects. For each case, the numbers shown in the matrix represent the hours of unserved energy from a subset of the 1008 random draws of solar and unit outages are shown. As the matrices indicate, many draws do not have any capacity shortfall events. On average, the number of hours with outages increases by 82% when AES is retired and only replaced with Stage 1 resources.

For each case, the outage rates of all 1008 random draws are summarized into a single metric, the average loss of load expectation (LOLE) value. Additional metrics such as 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 are also obtained in this analysis. Figure 2 on the following page shows the average LOLE for each of the eight cases. LOLE (y-axis) is plotted against increasing solar + storage

Outage Draws

Solar Years

Solar Year	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

Base Case

Solar Year	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

Figure 1. Example of Loss of Load Hours by Solar Years and Outage Draw.

adoption (x-axis). Low values represent lower risk of capacity shortfall. The dashed red line at the bottom of the chart represents the Reference Point, the calculated LOLE of the current system before the AES retirement and without additional solar + storage. The black line represents system reliability after the AES retirement with increasing amounts of solar + storage, including deferred maintenance, and the dashed line shows what the reliability level would be without deferred maintenance.

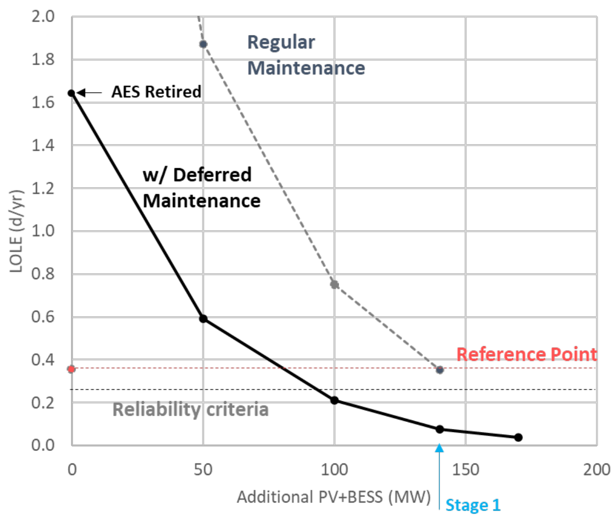

Figure 2. Loss of Load Expectation with Increasing PV+BESS.

While the figure clearly shows the unacceptable reliability with the AES retirement without additional solar + storage, much of that loss of reliability occurs in early months following the AES retirement and is recovered with the installation of just the Stage 1 solar + storage. This highlights the importance of project timing. The annual assessment shown in Figure 2 does not address the specific month-by-month timing of capacity additions and potential delays.

To further analyze the timing risk of replacement resources, the annual results shown in Figure 2 were evaluated on a monthly basis. HNEI developed a monthly screening tool to assess system reliability that could be adjusted with changes to commercial online dates and project delays. An example of this analysis is provided in Figure 3, but given the dynamic nature of project commissioning and delays, this analysis is routinely updated. The results show elevated risk throughout September and diminishing to zero as long as the standalone Kapolei storage project, or other solar + storage projects come online as planned.

The monthly assessment also showed that while ~40 MW of additions and deferred maintenance would bring the system back to current reliability levels, an additional 60 MW would be required by the next summer to bring the *annual* reliability for the September 2022 - August 2023 period back to the reference point if maintenance schedules return to normal.

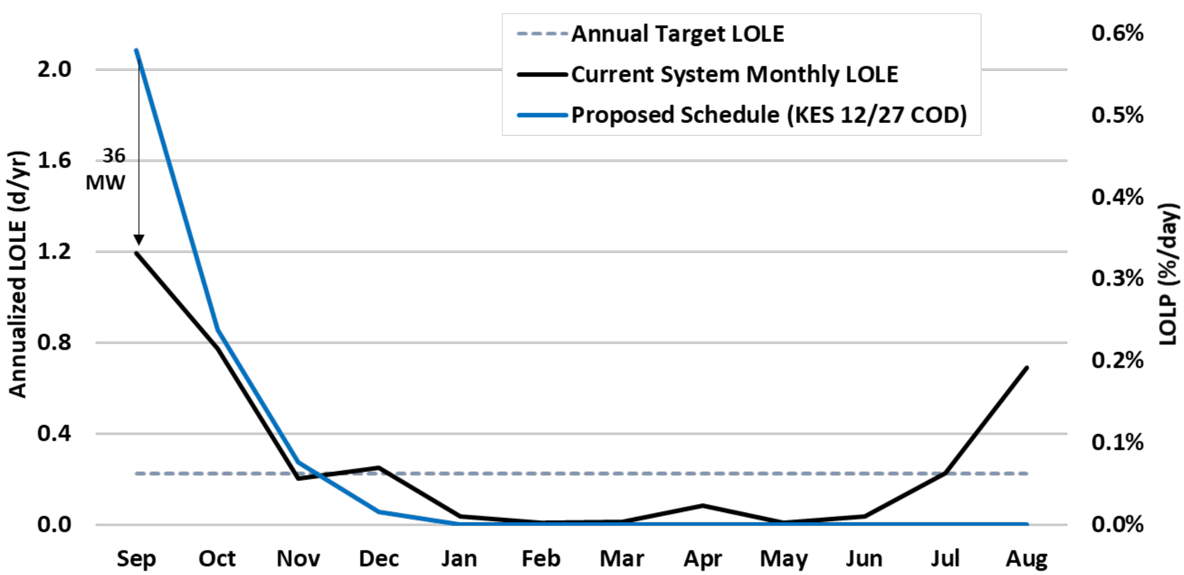

Figure 3. Monthly Annualized LOLE with Proposed Commercial Online Dates

The screening tool was provided to the governor's Power Past Coal task force to allow users to change commercial online dates of projects to screen for periods of increased reliability risk.

Information on outage size, frequency, and duration has been shared with the HPUC and DER parties to help design an emergency demand response program. Results showed that 70% of all resource adequacy events could be covered by a 60 MW, 2-hour resource available during evening hours and that number increased to 85% of all events with 100 MW of resources. Using this information, the HPUC developed a 50 MW emergency DR program requested aggregated battery energy storage systems for reliability.

In summary, with the addition of as little as 10% of the Stage 2 solar + storage projects - or the addition of the standalone Kapolei battery storage project - capacity shortfalls are eliminated altogether.

Recently announced delays of Stage 1 and Stage 2 projects indicate buildout of Stage 1 by the time AES is retired may be substantially under 100MW. HNEI participates in the Governor's Powering Past Coal Task Force and continues to monitor ongoing changes in deployment schedules.

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

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Last Updated: November 2021

A5: AES Biomass Conversion

OBJECTIVE AND SIGNIFICANCE: The Oʻahu coal plant operator, AES Hawaiʻi, has put forward a proposal to the Hawaiʻi Public Utilities Commission (PUC), HECO, and the Hawaiʻi State Energy Office (HSEO) to convert the plant to biomass sourced from North America. During initial community discussions of this possible conversion, concerns were raised regarding its cost, impact on future solar development, and need for such a plant on the Oʻahu grid. Following these discussions, HNEI undertook a study to better characterize the potential and the impacts of such a conversion. The objective was to provide unbiased information about the conversion and, if warranted, to facilitate additional discussions within the community.

KEY RESULTS: HNEI's analysis of the conversion of the AES coal plant to use biomass addressed several issues including:

- **RPS/Energy**: potential for significant contribution to the state's RPS goals without need for new transmission infrastructure.
- **Impact on Future Solar Development**: generation using biomass would not impact the ability to utilize additional solar energy
- **Resource Adequacy/Capacity**: firm generation would provide capacity reliability while enabling additional fossil retirement
- **Cost**: cost of the biomass energy can be comparable to fossil fuel. Avoided costs for fossil fleet operations and maintenance also need to be considered.
- **Emissions**: detailed life-cycle analysis required to assess net avoided CO_2 emissions

While electricity produced by the converted AES Biomass plant would be at a higher cost than recent hybrid solar and storage resources, the expected energy cost is sufficiently competitive with current fossil generation to warrant more detailed studies. Additionally, it was found that the plant could provide a large contribution (up to 20%) towards the state's renewable portfolio standard (RPS) while also providing firm capacity for Hawaiʻi's energy transition. Significantly, conversion of the AES coal plant was found to not limit further solar development across the island. Specifically, it was found that all of Stage 1 and Stage 2 plus another allotment of solar, larger than Stage 1 and Stage 2 could be accommodated without any significant curtailment.

To put this RPS contribution in perspective, energy from the AES Biomass plant would be roughly equivalent to that from 650 MW of utility-scale solar PV, more than all the utility-scale PV installed on Oʻahu after Stage 1 and Stage 2 is complete. Similarly, it would equate to more than double the amount of rooftop PV installed over the past ten years, equal approximately to having solar on every single-family home on Oʻahu.

While conversion to biomass would result in a substantial reduction of GHG emissions from fossil sources, a detailed assessment of the proposed biomass sources would be needed to quantify actual savings. This was beyond the scope of this initial study.

BACKGROUND: The AES coal plant is Oʻahu's largest generator and currently represents 15-20% of the utility's annual generation. The plant's retirement, scheduled for September 2022, will decrease the amount of dispatchable thermal capacity available to the utility by more than 10%. The retirement of the coal plant will end the use of coal for electricity generation in Hawaiʻi. To make this transition permanent, Hawaiʻi 2020 Act 23, Senate Bill 2629, prohibits new or renewed power purchase agreements for electricity generated from coal and prohibits the issuance of air permits for coal burning power plants on December 31, 2022.[1]

HECO is currently procuring a portfolio of hybrid solar + storage sources, as well as standalone storage to replace the coal plant's capacity and energy. These resources were procured via the utility's competitive bidding framework and are collectively referred to as the Stage 1 and Stage 2 projects. While many of the solar and storage resources were proposed to be available prior to the AES coal plant retirement, delays in the development, PPA negotiations, interconnection studies, and recent supply shortages have pushed out the commercial online dates of the replacement resources until after the coal plant

[1] Hawaiʻi State Legislature, SB2629 SD2 HD1, https://www.capitol.hawaii.gov/Archives/measure_indiv_Archives.aspx?billtype=SB&billnumber=2629&year=2020

retirement and PPA expiration. The impact of the AES retirement on resource capacity on Oʻahu is the subject of another study conducted by HNEI and included in this report.

To facilitate discussions and data collection the PUC opened a proceeding to review the status of AES retirement and the interconnection of replacement resources.[2]

As a result of this proceeding, the HSEO created the Powering Past Coal Task Force to "convene stakeholders to increase transparency, coordination, collaboration, and urgency to timely facilitate, coordinate, and align project development and reviews by Hawaiian Electric, state, and county agencies for those measures anticipated to provide electricity for Oʻahu to replace the coal plant's electricity…"[3] One option that was considered by the Task Force was a conversion of the AES plant to operate with a biomass fuel source. At the request of the Task Force chair, AES Hawaiʻi, LLC put forward a proposal to continue the use of coal at AES through the remaining three months of 2022 to provide grid reliability and then convert to biomass operations in 2023.[4]

According to AES Hawaiʻi, "Depending on the length of time biomass would be expected to be used, AES could consider different conversion options and different power purchase agreement ("PPA") terms. We expect such a biomass project could support Oʻahu's needs for a successful energy transition, and at a lower cost to consumers. Our current all-in cost estimates to operate on biomass are between approximately 0.18-0.20 cents/kWh, subject to additional engineering work, update in equipment pricing, availability and cost of biomass pellets, permitting costs and timeline, and the expected capacity factor, as well as the Commission-approved PPA terms between Hawaiian Electric and AES."

PROJECT STATUS/RESULTS: To better understand the role of biomass and the AES conversion in Oʻahu's future energy mix, the HNEI team conducted a cost-benefit feasibility analysis of the proposed conversion. This analysis included hourly PLEXOS production cost simulations comparing cases with and without the AES Biomass conversion. Production cost models simulate grid operations on an hour-by-hour (or sub-hourly) basis across an entire year. The simulations included detailed operating characteristics of the generation mix, fuel prices, wind and solar resource availability, hourly load, and transmission constraints. A series of cases were evaluated across a wide range of potential AES operations (from 2% to 90% annual capacity factors). The cases with and without the AES conversion were then compared to quantify RPS contribution, assess the impact on future solar development and curtailment, evaluate its contribution to resource adequacy (grid reliability), identify costs or cost benefits, and quantify emissions saved from the avoided fossil fuel.

In order to quantify the costs and benefits of the AES Biomass conversion across range of future system conditions, two scenarios of grid operations were evaluated. A resource mix consistent with the IGP 2024 plans which included all the approved Stage 1 and Stage 2 solar and storage resources under development, as well as HECO's forecast of continued distributed energy resource additions was evaluated. Fuel and load assumptions from HECO's IGP forecast were also included.

A second analysis was also conducted to evaluate the impacts of the AES conversion with a larger solar resource mix. For this study, HNEI used assumptions for 2030 but also assumed an additional "Stage 3" tranche of 400 MW of utility solar with1600 MWh of storage plus an additional 100MW of DER growth (relative to 2024).

Fuel prices were held constant between the two simulations to allow for direct comparisons, and fuel price sensitivities were conducted separately to identify costs across a range of potential oil prices. Lastly, both sets of runs assumed the proposed retirement of Waiau units 3-6, with additional

[2] Hawaiʻi Public Utilities Commission, "Opening a Proceeding to Review Hawaiian Electric's Interconnection Process and Transition Plans for Retirement of Fossil Fuel Power Plants," Docket No, 2021-0024.
[3] Hawaiʻi State Energy Office, "Power Past Coal Task Force," https://energy.hawaii.gov/ppctf
[4] AES Hawaiʻi, LLC, "Letter from J. Bigalbal to the Hawaiʻi Public Utilities Commission," Dated June 16, 2021, Docket No. 2021-0024, https://dms.puc.hawaii.gov/dms/DocumentViewer?pid=A1001001A21F17A84517B00533

retirements evaluated in the resource adequacy analysis. The primary tool used in these analyses was PLEXOS, a commercially available production cost model. The reliability analysis also used PLEXOS, but in a stochastic manner that was described in last year's report.

PS/Energy: biomass conversion could provide a large contribution towards the state's RPS

Results of the production cost analysis indicate that AES Biomass could operate across a wide range of potential use cases, operating as a reliability-only asset (2% capacity factor) up to full energy output (90% capacity factor). In these cases, shown in Figure 1 below, nearly all displaced generation occurs on HECO's steam oil fleet, namely the Kahe units 1-6 and Waiau units 7-8 reducing both fuel costs and fossil emissions. The Waiau 7 and 8 units were used sparingly with the AES conversion, indicating that both units are candidates for future retirement and thus were evaluated in subsequent resource adequacy analysis.

The RPS benefits assume that the biomass meets the state's definition of renewable energy, is sustainably sourced, and meets low carbon life-cycle requirements. The AES plant operating on biomass could produce up to 1,500 GWh of electricity per year. This represents approximately 20% of the island's sales and RPS requirement, after reducing for behind the meter PV and transmission losses. The RPS contribution across a wide range of capacity factors, and in both the 2024 and 2030 resource mixes is shown in Figure 2. To put this RPS contribution in perspective, energy from the AES Biomass plant would be roughly equivalent to that from 650 MW of utility-scale solar PV, more than all the utility-scale PV installed on O'ahu after Stage 1 and Stage 2 is complete. Similarly, it would equate to more than double the amount of rooftop PV installed over the past ten years, equal approximately to having solar on every single-family home on O'ahu.

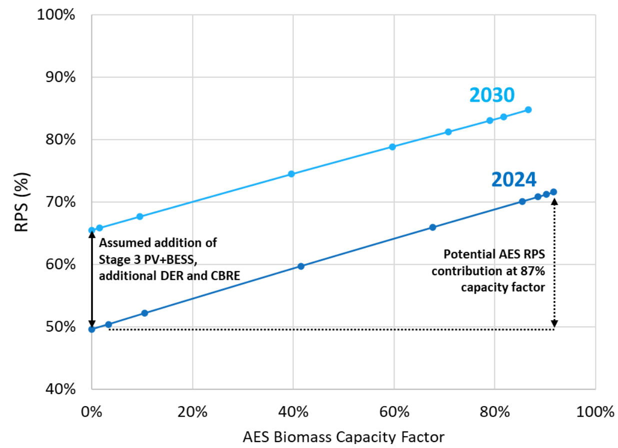

Figure 2. RPS Contribution of AES Biomass in 2024 and 2030.

Significantly, this gain toward achieving the state's RPS goals would not require new transmission infrastructure. The plant is situated in the Campbell Industrial Park, with multiple 138 kV high-voltage paths interconnecting to load centers in Honolulu. The transmission infrastructure on the leeward side of the island was designed to transfer power from two-thirds of the island's thermal capacity (AES, Kalaeloa CC, CIP CT, and Kahe plants) so there is adequate transfer capability. In addition, this region of the island does not have many suitable sites for solar PV development, so use of the existing transmission

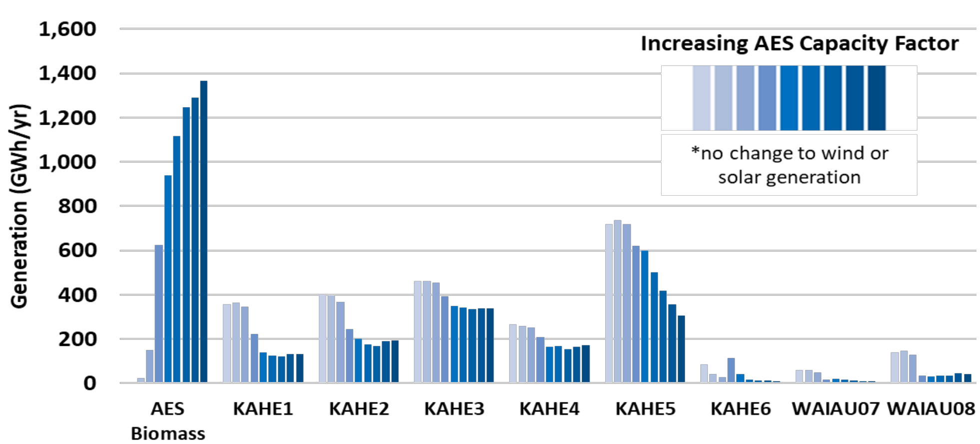

Figure 1. Generation by AES Relative to Steam Oil Displacement.

infrastructure would not conflict with future solar development needs.

Impact of Future Solar Development: AES Biomass would not impact future solar development

The production cost analysis used to quantify unit operations for the two solar scenarios, with and without biomass, also provide detailed information on the utilization of the deployed solar systems. Most notably, under neither of these scenarios was there an increase in curtailment of wind or solar resources. This indicates that even at high output, the conversion of AES to biomass would not interfere with ongoing plans by the utility, developers, and stakeholders to economically interconnect new solar PV resources to the grid. In the cases with the highest AES utilization, there was a modest increase in battery cycling, indicating that solar was put through battery storage systems to be utilized later in the evening hours rather than going directly onto the grid in the middle of the day.

Resource Adequacy: biomass conversion would provide capacity reliability and resource adequacy

As discussed above, the original genesis of the AES Biomass conversion proposal was based on a plan to continue coal operations through 2022 to help meet reliability needs until adequate Stage 1 and Stage 2 solar and storage projects come online.

In this work, the HNEI-Telos Energy team examined reliability and resource adequacy benefits in a future context, longer term operation on biomass to support reliability and possibly the retirement of additional steam oil units.

To evaluate the resource adequacy contribution of the AES Biomass plant, a resource mix that included all of Stage 1 and Stage 2 plus an additional Stage 3 (400 MW of PV+BESS resources) was evaluated with incremental retirements of thermal generation. Each case was evaluated across 504 randomly generated samples that evaluated various weather years and thermal generator outages. The analysis quantified the number of times when the system did not have sufficient capacity available to serve load (referred to as a loss of load event).

Figure 3 shows the loss of load expectation (LOLE days/year), with and without conversion of the AES plant, for various retirement scenarios including Waiau 3-8 and Kahe 1-2). The analysis shows that full solar deployment of Stages 1-3 and the operation of AES allows for the full retirement of the Waiau plant, and one additional steam oil unit. Without AES, the retirement of just the Waiau plant puts reliability near the historical reliability criterion of 0.22 days/year. The addition of the 180 MW biomass plant enables a retirement of 140-160 MW of aging steam oil capacity beyond that without AES.

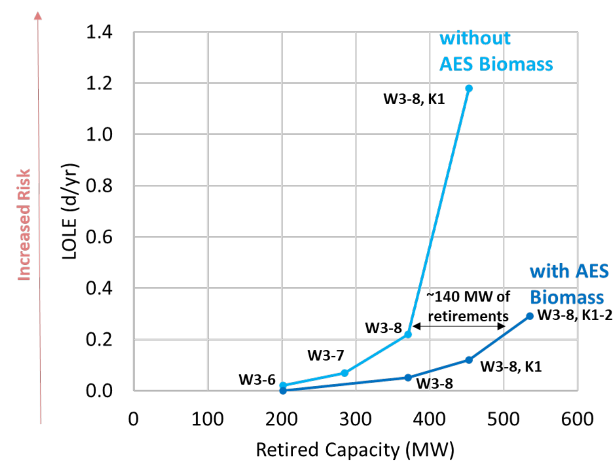

Figure 3. Reliability Risk with and without the AES Conversion.

The biomass plant does not provide a full one-to-one replacement of steam oil units due to the larger size of the AES unit. However, this analysis made the conservative assumption that any outage at AES would take the full plant offline. In practice, the AES plant has two separate boilers, and while a full outage is possible, it is more likely that the plant would be partially de-rated rather than experience a full outage.

The HNEI-Telos Energy team is initiating a detailed modeling effort to quantify firm power requirements under various very high variable renewable scenarios, including continued development of solar and offshore wind.

Emissions: biomass conversion significantly reduces emissions from fossil fuels

The avoided oil consumption from the AES Biomass plant significantly reduces GHG emissions from oil, thus offering an opportunity for to emissions benefits. The net GHG reduction achievable by converting to biomass requires a full lifecycle analysis for the plant, fuel, and all transportation components. Biomass does have significant direct emissions when it is burned for electricity generation. However, the lifecycle of the biomass fuel also absorbs CO_2 in the atmosphere as the biomass is grown. Whether or not the lifecycle of the biomass is low carbon depends on the type of biomass, harvesting techniques, transportation, and whether the locations used for biomass harvesting are replanted.

While lifecycle analysis of biomass feedstock was not in the scope for this study, the HNEI team, as part of a separate request from the PUC, reviewed a large set of peer-reviewed studies for biomass combustion. This review indicates the potential for significant reductions in GHG compared fossil fuel use when full lifecycle emissions are considered.

Cost: biomass as a hedge against future oil price volatility

The cost benefits of any renewable project added to the O‘ahu grid will depend on the avoided generation from existing thermal resources and displaced steam oil generation. These costs include reduced fuel consumption, avoided variable operations and maintenance (VO&M), and startup and shutdown costs. Because these generation costs are primarily (i.e. >95%) attributed to reduced fuel costs, they are referred to throughout this section as avoided fuel savings.

As shown previously in Figure 1, operation of the AES biomass generation would displace energy from the existing steam oil fleet. While increased generation from AES would increase the utility’s total PPA payment, these costs would be at least partially offset by savings from reduced oil consumption. At a $70/bbl price of oil, the total production costs with the AES Biomass conversion are higher by approximately $55 million per year, regardless of how much the plant runs. This is because the variable cost component of the AES Biomass (i.e. fuel cost and O&M expenses) is roughly equal to the steam oil variable cost at $70/bbl, with the remaining costs attributed to the fixed capital cost for the conversion.

At this oil price, the AES conversion would add approximately 0.75 cents/kWh to ratepayers. For an average residential customer who uses 500 kWh per month, this is equal to $3.70/month (or a 2.4% increase). A table of the AES payments, avoided costs, and net benefits are provided in Table 1 across a range of AES utilization.

However, global oil prices are volatile. Over the past 10 years, oil prices have ranged from a low of $29/bbl in 2016 (excluding negative pricing during the COVID-19 pandemic) and a high of $112/bbl in 2011. Over the past five years, prices have fluctuated between $50-85/bbl. Because Hawai‘i imports oil for most of its electricity consumption, the state’s residents and utility customers are exposed to this fuel price volatility. Biomass, on the other hand, can be contracted on a long-term basis with fixed fuel costs.

	Property	**$70/bbl Oil Price**				**$100/bbl Oil Price**			
AES Utilization	AES Capacity Factor (%)	**0%**	**40%**	**60%**	**87%**	**0%**	**40%**	**60%**	**87%**
	AES Generation (GWh)		625	941	1,366		625	941	1,366
	RPS Contribution (%)		8%	13%	19%		8%	13%	19%
AES Payments	AES Energy Payment (k$)*		76,614	113,358	163,225		76,614	113,358	163,225
	AES Capacity Payment (k$)		54,000	54,000	54,000		54,000	54,000	54,000
	Total AES Payment (k$)		130,614	167,358	217,225		130,614	167,358	217,225
	Total AES Payment ($/MWh)		209	178	159		209	178	159
System Costs	HECO Production Costs (k$)**	**475,510**	**399,990**	**366,187**	**313,265**	**672,403**	**564,672**	**516,448**	**440,810**
	Avoided Costs (k$)		75,520	109,323	162,245		107,731	155,955	34,699
	Avoided Costs ($/MWh)		121	116	119		172	166	25
	Total Production Costs (incl. AES) (k$)	475,510	530,604	533,544	530,490	672,403	695,286	683,805	658,036
Net Benefits	**Net Benefits (Costs) (k$)**		-55,094	-58,035	-54,980		-22,883	-11,402	14,367
	Net Benefits (Costs) ($/MWh of AES)		-88	-62	-40		-37	-12	11
	Net Benefits (Costs) (c/kWh of sales)		-0.7	-0.8	-0.7		-0.3	-0.2	0.2

*Energy Payment = Fuel + VO&M costs, based on utilization

**Includes fuel costs and VO&M costs for HECO generation and Kalaeloa CC. Does not include AES costs or renewable PPAs, or other fixed costs

Table 1. Avoided Cost Calculations for AES Biomass Conversion at Increasing Utilization.

Figure 4 illustrates the net benefits (costs) of the AES Biomass conversion across a range of oil prices, from \$50/bbl to \$120/bbl. This indicates a break-even cost at \$100/bbl of oil, and costs ranging from 0.5 cents/kWh to 1.2 cents/kWh with oil prices between \$50-80/bbl.

Figure 4. Cost of AES Biomass Conversion at Varying Oil Prices.

It should be noted that this cost-benefit analysis only includes the avoided energy benefits for the reduction in fuel use. It does not include other potential benefits attributed to the AES conversion, including capacity reliability benefits, emissions reductions, reduction in land use, etc.

It should also be noted that a portion of the biomass required for this plant could be locally sourced. The jobs growth and increased self-sufficiency of the islands has not been considered in this analysis.

Conclusions

The results of this feasibility study indicate that further consideration of biomass in O‘ahu's energy future is warranted. The AES biomass conversion would significantly accelerate O‘ahu's clean energy transition without inhibiting or delaying the continued growth of solar resources (both distributed and utility-scale). Since this project would largely use existing infrastructure, it is expected that the contract length for the biomass operations could be flexible. This has the potential to be a low-regret option to achieving a large increase in renewable energy without excluding new renewable resources that may be developed in the future.

Two issues, however, do require more in-depth study. The costs of the proposed AES biomass conversion are based on this preliminary analysis are high relative to other resource types. However, low cost solar cannot get us to 100%. Other fully dispatchable resources (new or existing) will be needed. Secondly, while it is clear that use of biomass will significantly reduce GHG emissions from our fossil fleet, the net benefits of this transition requires a full life-cycle assessment of the plant conversion and potential fuel sources.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2021

A6: DER Aggregation and Control with High Penetration Solar + Storage

OBJECTIVE AND SIGNIFICANCE: Over the past decade, the O‘ahu power grid has integrated substantial amounts of solar PV. With over 550 MW of uncontrollable and unobservable distributed PV, and 190 MW of utility-scale PV installed, there was limited available room on the grid for further solar deployment without energy storage. However, recent developments, including the planned retirement of the AES coal plant, the expected addition of large amounts of battery storage, and new options for grid flexibility, have created new opportunities to integrate distributed rooftop PV. The objective of this study was to quantify how much room may be available on the grid (referred to as system hosting capacity) for additional DER resources. A second objective of this analysis was to provide understanding how much aggregation and direct control is necessary in a high solar grid.

KEY RESULTS: Results of this analysis indicate that the O‘ahu grid can host roughly 600 GWh of additional distributed solar resources without energy storage before curtailment becomes appreciable. On a capacity basis, this represents approximately 400 MWac of distributed PV. Deployment of distributed PV beyond this amount could lead to significant curtailment of utility-scale resources, potentially impacting the viability of existing and future utility scale projects, and increased costs to ratepayers without rooftop PV.

Distributed PV offers a solar pathway that can defer transmission upgrades due to its proximity to load and reduce land use. The pairing of storage with distributed PV would allow for higher amounts to be accommodated. While shifting solar energy out of the middle of the day is necessary, results indicate that direct aggregation and control of distributed resources does not provide significant value to the system. Specifically, more passive and autonomous controls at the customer level provides substantial grid support without the need for costly communications, control systems, and payments for DER grid services.

BACKGROUND: Over the past 10 years, the O‘ahu power grid has experienced rapid growth of renewables. Following modest utility scale wind development, this growth has been mostly in solar PV additions. The first several years, driven by high utility costs, net metering and large state tax credits; were predominately distributed rooftop PV (DPV) systems, resulting in approximately 550 MW of DPV on a 1000 MW mid-day load system. This growth made the Hawai‘i grids one of the highest distributed solar markets in the world as a percentage of total load. However, in recent years, this growth has slowed considerably due to changes in the rate structure and due to integration challenges at both the system and circuit-levels.

As the growth of DPV was slowing, a limited amount of utility scale PV, without storage, was deployed. At the conclusion of these Waiver PV projects, the O‘ahu grid was largely limited in the amount of additional PV that could be integrated effectively without storage.

To overcome the curtailment and saturation concerns, the Hawai‘i Public Utilities Commission (PUC) approved, in 2018, fifteen utility-scale hybrid solar and storage (solar + storage) projects. These projects, often referred to as Stage 1 and Stage 2 resources, total approximately 670 MW solar and 3,538 MWh of storage statewide that includes up to 415 MWac solar and 1,781 MWh of hybrid storage on O‘ahu as well as what will become one of the largest standalone battery storage systems anywhere in the world: the 185 MWac and 565 MWh storage system to be located in Kapolei. The projected renewable energy use on O‘ahu, based on the RPS definition, through the Stage 2 projects, is shown in Figure 1.

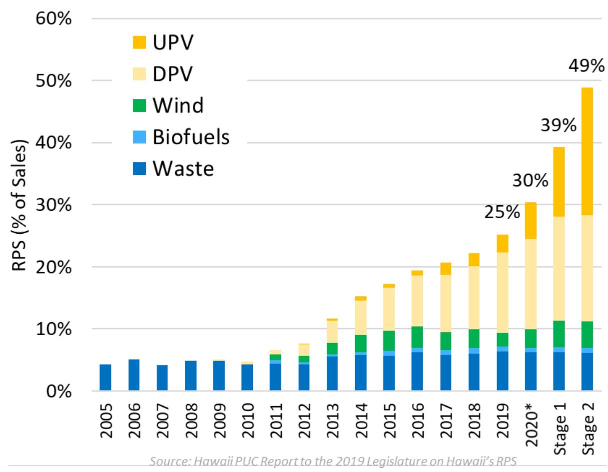

Figure 1. O‘ahu RPS Growth 2005-2020, and Stage 1+2.

These changes are taking place against the backdrop of other significant change to the grid that could enable further solar deployment. Most notably are the retirement of the AES coal plant, the largest fossil fuel-based generator on the O'ahu grid and the addition of the standalone Kapolei battery that can charge during the day using surplus solar resources. These storage systems, both the PV connected and the stand-alone Kapolei BESS, can also provide grid services that were traditionally provided by the steam oil fleet. As a result, the grid will soon be significantly more flexible than a traditional system.

PROJECT STATUS/RESULTS: In this work, analysis was conducted to evaluate the need and value of aggregation and control for additional distributed solar + storage (DER) deployments. In order to quantify this value, a series of production cost grid simulations were conducted at increasing solar penetrations, with increasing 100 MWac blocks of installed distributed solar capacity. Each PV block was added with two different storage capacity configurations shown in the table below. These configurations are based on HECO's IGP forecast for DER solar + storage resources (#1) and a review of commonly configured behind the meter residential PV and storage systems used in Hawai'i (#2).

	PV Capacity (MW)	BESS Capacity (MW)	BESS Energy (MWh)	BESS Duration (hrs.)
#1	100	30	96	3.2
#2	100	77	154	2.0

The simulations were conducted assuming the completion of Stage 1 and 2 projects, the retirement of AES coal plant, and the retirement of HECO's Waiau 3 and 4 generators. The net impact of these resource changes would increase the system hosting capacity.

The production cost models simulate grid operations across all 8,760 hours per year, and incorporate fluctuating loads, solar, and wind resources. The remaining grid resources, including thermal generation and battery energy storage, are economically scheduled to serve load in a least-cost manner subject to utility defined operational limitations and transmission constraints. If the underlying generation mix does not have ample flexibility (either storage to charge using surplus solar or ability of thermal generators to cycle offline) solar may be curtailed and unused.

The benefits of DER aggregation and control were evaluated by simulating two bookend scenarios, illustrated in Figure 2. In actual practice, DER aggregation and control would likely fall somewhere between these two bookend points, but the analysis was conducted using assumptions on either end of the DER control spectrum to amplify potential differences between the two approaches.

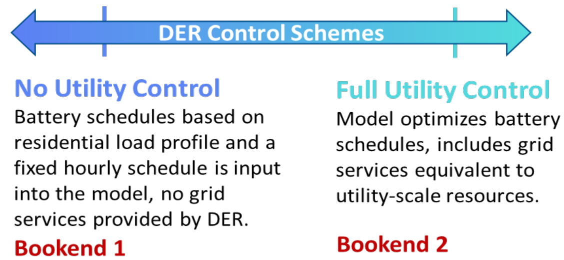

Figure 2. Overview of DER Control Schemes.

The simulations first assumed that DER resources were fully controllable and dispatchable by the system operator. Following that, cases were reevaluated assuming the DER followed a fixed schedule and could not deviate based on system conditions.

The resulting incremental solar curtailment, assuming full control, with increasing solar deployment is provided in Figure 3. Results are shown assuming no storage and for the two storage configurations described above. Incremental curtailment is the increase in curtailment relative to the amount of available PV energy resulting from the last block of additional capacity. As additional PV is added to the grid, not all of it can be accepted, even when combined with the storage configurations that were evaluated.

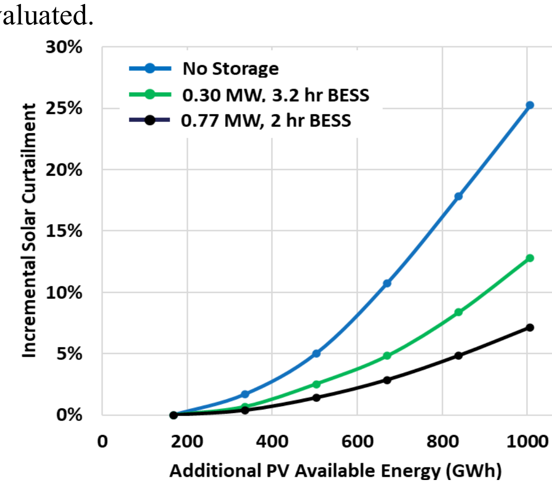

Figure 3. Solar Curtailment at Increase Deployment.

It should be noted that with 4-hour storage with a 1:1 battery to solar configuration, all curtailment is eliminated. In practice, although this study assumes the addition of DER, curtailment would likely be applied to the available utility-scale projects, not the new distributed systems.

At the other end of the spectrum (bookend 2), cases were reevaluated assuming the DER followed a fixed schedule and could not deviate based on system conditions. This schedule was based on a simple heuristic that combined existing utility time of use rates, discharging rules associated with the utility's Smart Export Program, and the average system net load curve. This schedule assumed the following constraints and is illustrated in Figure 4:

- Battery charging occurs between 9 AM and 5 PM, and most charging occurs during the lowest net load hours (during mid-day solar availability);
- Battery charging is limited to the associated rooftop PV production;
- Battery discharging occurs between 5 PM and 10 PM, and is highest during the peak net load hours; and
- Total battery utilization is limited to one cycle per day.

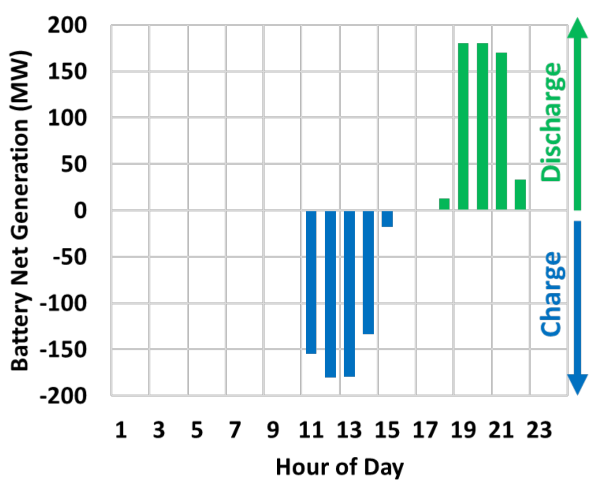

Figure 4. Average daily battery schedule for DERs.

The results, provided in Figure 5, indicate that there are no differences in curtailment between cases with full utility control and when systems follow a fixed profile. This is because there is ample flexibility on the remaining utility-scale hybrid solar + storage resources to adjust to the static DER profile.

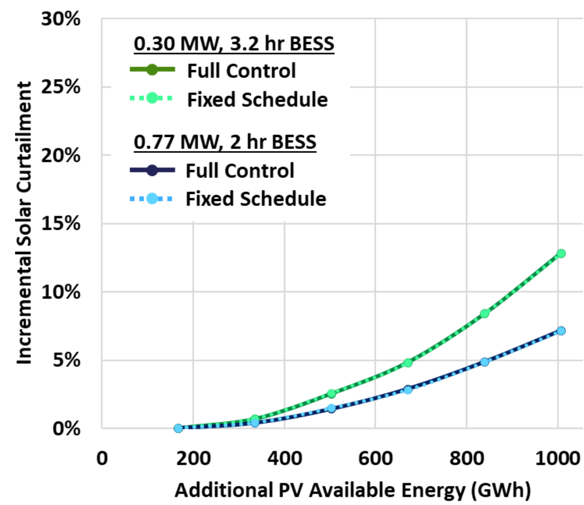

Figure 5: Curtailment of solar resources with and without utility control.

In addition, the results showed no appreciable difference in total system generation cost (less than 0.1%) because there was no change in oil-fired generation and grid services were already saturated by the utility-scale storage systems.

These results support two key conclusions. First, there is limited need for direct communication and control of DER resources to avoid system curtailment of utility-scale solar resources. As long as behind the meter storage shifts energy out of the middle of the day via a simple rules-based approach (i.e. the utility's Smart Export program), curtailment can be effectively mitigated. Second, there is no economic benefit of DER control and coordination once there is sufficient utility-scale storage resources available on the system. The flexibility and grid service benefits saturate once a certain amount of battery storage is installed on the system.

From a policy and regulatory perspective, this indicates that programs to require or compensate DER resources for coordination and control may not be necessary or warranted once sufficient grid scale storage is available to the system operator and that well designed tariffs and autonomous response of DER to grid conditions (i.e. frequency or voltage response) are sufficient for further DER integration.

It should be noted that these findings are specific to the Oʻahu power system and are largely dependent on the amount of utility-scale storage systems present.

By the end of 2023, O‘ahu is expected to have 600 MW (2,400 MWh) of utility-scale storage installed with direct utility control capability. This is relative to a ~1200 MW peak load system. Thus, incremental value for additional flexibility and grid services is limited.

It should also be noted that this analysis did not evaluate benefits of DER coordination and control that might be important for circuit-level hosting capacity constraints, which may be a limiting factor for future DER installations at specific locations. Future work is planned to address this.

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

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Last Updated: November 2021

A7: Maui Reliability and Kahului Retirement Analysis

OBJECTIVE AND SIGNIFICANCE: The Kahului Power Plant (KPP), one the oldest steam oil plants on Maui, is scheduled to retire by the end of 2024. This retirement has been proposed for over a decade but has been delayed due to projected system reliability challenges. The objective of this study was to evaluate the ability of proposed utility scale solar + storage resources to maintain grid reliability when KPP is retired. The results of this analysis were briefed to the Hawaiʻi Public Utility Commission (PUC) and other stakeholders and are expected to have important implications for power system planning and policy for Maui.

KEY RESULTS: Stochastic analysis, using the tools developed by the HNEI-Telos Energy team that have previously been used to evaluate resource adequacy of the Oʻahu grid, was conducted. It was found that the KPP retirement without deployment of other generation sources would significantly reduce system resource adequacy as measured as loss of load expectation (LOLE). However, the analysis showed that deployment of even a small portion of the proposed hybrid solar + storage projects would improve system reliability compared to current reliability levels. Full deployment of proposed Stage 1 and Stage 2 solar + storage resources would significantly improve system resource adequacy compared to current operations.

The number and size of proposed replacement projects, the retirement timeline, and the ability to extend KPP operation, if necessary, makes the reliability risk on Maui significantly lower than that associated with the Oʻahu coal retirement plans.

BACKGROUND: KPP is a 36 MW steam oil power plant located in Kahului, Maui. It is comprised of four separate steam oil generators and is over 72 years old. Maui Electric Company (MECO) has frequently proposed retirement of the plant over the past decade, but had not been able to develop and procure replacement resources due to project delays and regulatory limitations. Currently, there is a proposed transition plan by the utility comprising deployment of utility scale solar + storage hybrid resources and upgrades to the transmission system. According to Hawaiian Electric:

"The KPP Transition Plan has several key components: (1) the Stage 1 and Stage 2 RFP projects will provide capacity and energy replacement and grid services; (2) the K3 and K4 generating units of KPP will be converted and repurposed to synchronous condensers to replace critical voltage support service and synchronous inertial response provided by KPP, among other essential grid services; (3) the Waena Switchyard project will maintain functionality and reliability of the transmission system serving Maui in the absence of KPP, avoid circuit overloads, and reliably integrate new renewable resources; and (4) contingency plans that include DER grid service programs and a review of generator maintenance schedules as needed."[5]

Once complete, the Stage 1 and Stage 2 projects will significantly change the Maui system. The projects constitute 135 MW of solar with 540 MWh of storage along with a 40 MW, 160 MWh standalone battery in Waena. Projects are anticipated to come online between 2022 and 2023. Once complete, the Maui system will approach 100% RPS (as a percentage of sales) and 75% annual energy (as a percentage of total generation) from renewable resources. Expected annual energy generation based on RPS is shown in Figure 1.

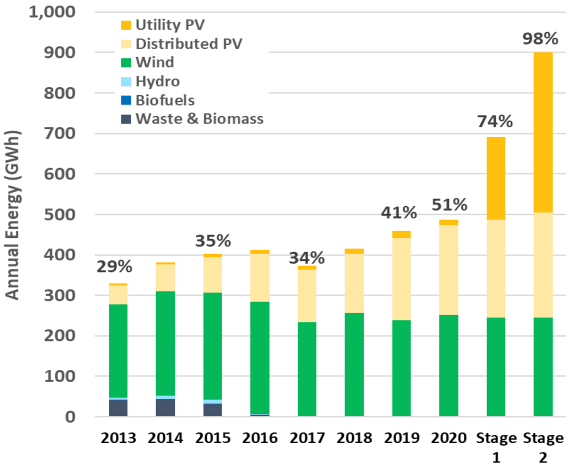

Figure 1. Maui Renewable Growth and RPS (%) by Year.

PROJECT STATUS/RESULTS: To assess the reliability (specifically resource adequacy) of the Maui system

[5] Hawaiian Electric Company, Kahului Power Plant Transition Plan, Docket No. 2021-0024, April 5, 2021, https://dms.puc.hawaii.gov/dms/DocumentViewer?pid=A1001001A21D06A91020A00146

with the KPP retirement and replacement solely with variable renewable energy and energy storage, HNEI and Telos Energy utilized its sequential Monte Carlo probabilistic modeling, which incorporated 22 years of chronological solar data, 8 years of chronological wind data, and 12 years of historical outage data for the thermal generators. This is the same probabilistic methodology used to evaluate the AES coal plant retirement on Oʻahu).

Grid simulations were conducted across four scenarios with assumptions on load, DER integration, and other system details derived from HECO's Integrated Grid Planning assumptions for the year 2024. The Reference Point scenario assumed the current grid's resource mix, including KPP, without additional retirements or new solar resources. Three additional scenarios were evaluated: 1) with KPP retired without replacement, 2) with 75 MW Stage 1 resources, and 3) with another 60 MW of solar + storage and 40MW of standalone storage resources with the Stage 2 portfolio. Each of these scenarios are illustrated in Figure 2.

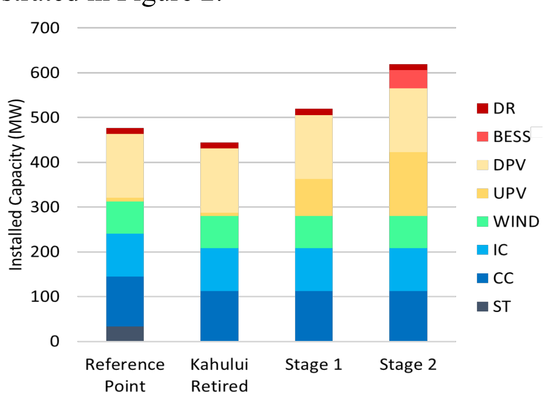

Figure 2. Installed Capacity by Scenario.

Each scenario was analyzed across 440 random samples (replications) of chronological dispatch, representing 22 years of solar data, 8 years of wind data, and 20 outage profiles per weather year (440 total). 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.

Results of the analysis are provided in Figure 3 with the same data shown on both figures with the exception of the y-axis (normal vs. log axis respectively). These results indicate that any combination of ~40 MW of solar + storage or standalone storage resources brings the system back to its current level of reliability.

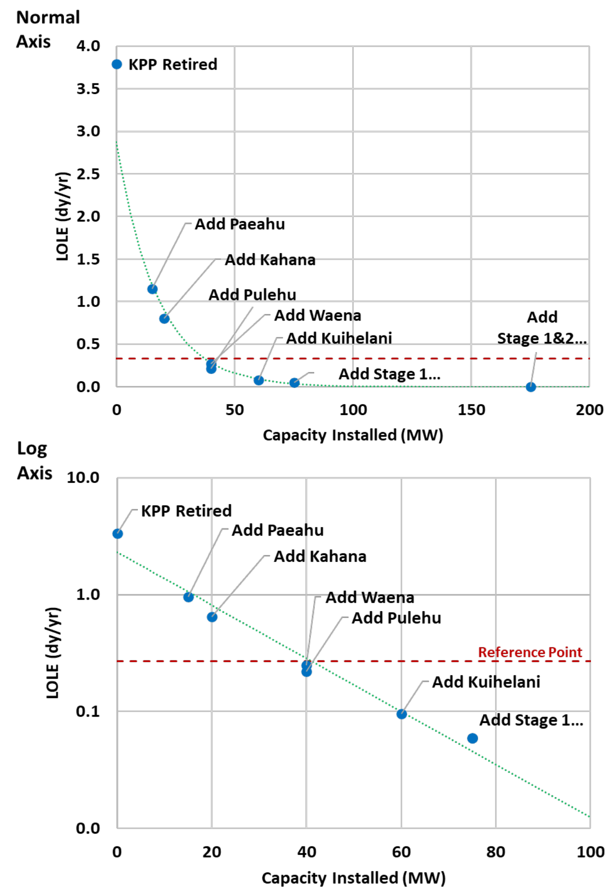

Figure 3. System LOLE at Increasing Levels of Solar + Storage.

Full deployment of Stage 1 and 2 resources eliminates all loss of load events in the resource adequacy simulations, indicating a much higher level or reliability relative to historical norms and a potential opportunity for additional retirement of fossil unit. The results also highlight an important finding, consistent with the results for Oʻahu, that solar and storage resources provide a near 1-to-1 replacement capability relative to thermal capacity on the system. While this relationship will not continue indefinitely, it highlights the ability for variable renewables and energy limited resources to provide firm capacity.

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

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Last Updated: November 2021

A8: Disposal and Recycling of Clean Energy Products in Hawaiʻi

OBJECTIVE AND SIGNIFICANCE: The objective of this study is to conduct a comprehensive study to determine best practices for disposal, recycling, or secondary use of clean energy products in the State. In recent years, Hawaiʻi has seen significant growth in the use of solar photovoltaic (PV) panels. This is expected to continue with new systems, both rooftop and utility scale, combined with battery energy storage systems.

This situation will produce significant waste over the next 20-30 years. The objective of this work is to quantify this waste stream to identify potential hazardous materials, as well as those that may offer opportunity for cost-effective recycle. Hawaiʻi, faces the dual concern of possessing limited disposal options while hosting a significant amount of installed PV and storage materials.

BACKGROUND: The 2021 Hawaiʻi State Legislature, passed House Bill 1333, which requires that the Hawaiʻi Natural Energy Institute (HNEI), in consultation with the Hawaiʻi State Department of Health, conduct a comprehensive study to determine the best practices for disposal and recycling of discarded clean energy products in Hawaiʻi. Specific outcomes are to address: 1) the amount of PV and solar water heater panels in the State that will need to be disposed of or recycled, 2) other types of clean energy materials expected to be discarded in the State including glass, frames, wiring, inverters, and batteries, 3) the type and chemical composition of those clean energy materials, 4) best practices for collection, disposal, and recycling of those clean energy materials, 5) whether a fee should be charged for disposal or recycling of those clean energy materials, and 6) any other issues the Hawaiʻi State Energy Office and Department of Health consider appropriate.

PROJECT STATUS/RESULTS: This project commenced in September of 2021 and remains ongoing. Findings to date includes identifying material composition of PV panels, inverters, cabling, and mounting equipment as a function of installed power (kg/kW), cumulative installed PV by island for residential, commercial, and utility scale since 2005 the project loading rate of aging PV materials as far out as 2045, preliminary estimates of installed battery capacity as residential, commercial, and utility scale, and estimates of material composition of PV battery as a function of installed power (kg/kW).

Preliminary results have been summarized in a separate report to the legislature.

Funding Source: Energy Systems Development Special Fund

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Last Updated: November 2021

A9: Energy Transition Initiative Partnership Program (ETIPP)

Objective and Significance: The Energy Transition Initiative Partnership Program (ETIPP) is a three-year effort established and funded in late 2020 by the U.S. Department of Energy to provide analysis, technical assistance, and policy guidance to address high energy costs, reliability, and inadequate infrastructure challenges faced by island and remote communities. In December of 2020, HNEI was selected via a competitive solicitation as one of the first five regional ETIPP partners to provide technical assistance and support community engagement. The long-term objectives are two-fold: 1) solve critical questions and issues of importance by communities engaged in energy transitions; and 2) support replicable energy transition technical assistance and knowledge sharing to inform and support energy transitions throughout the United States.

Background: By understanding local energy and infrastructure challenges, goals, and opportunities, ETIPP's partner network is intended to empower communities to proactively identify and implement strategic, holistic solutions tailored to their needs. ETIPP provides technical assistance opportunities for remote, island, and islanded communities. Selected communities receive support for a project scoping phase (approximately one to two months), followed by 12- to 18-month-long energy planning and analysis projects that:

- Prioritize community energy values, goals, challenges, and opportunities;
- Identify and advance the ability to implement strategic, whole-systems solutions; and
- Foster high-impact, replicable community energy transition approaches.

By participating in ETIPP, communities can expect to receive substantial in-kind support from the national labs and regional partners in the form of technical expertise on energy analysis, planning and implementation, and program guidance and education from the regional partners.

Project Status/Results: During 2021, HNEI conducted outreach to identify qualified applicants interested in receiving technical assistance and was a key member of the evaluation team that selected two projects in the Hawai‘i region out of the 11 projects selected nationally for Cohort 1; one in Honolulu proposed by Hawaiian Electric Company (HECO), and one in Kaua‘i, proposed by the County of Kaua‘i.

The HECO project is intended to identify locations within its distribution service territory in Honolulu for hybrid microgrid development, a first in the United States by a utility. Hawai‘i is prone to severe weather conditions which have the potential to cause long-duration power outages. Hawai‘i has identified hybrid microgrids as one method to improve resilience. Under this project, Hawaiian Electric will work with the National Renewable Laboratory and its project team, including Sandia National Laboratory and HNEI, to develop criteria for evaluating hybrid microgrids less than 3MW on the island of O‘ahu, and create a map identifying potential locations given a set of criteria prioritized by stakeholders.

The County of Kaua‘i's "Electric Vehicle and Multi-Modal Transportation Transition" project supports the island's effort to eliminate fossil fuel use in the ground transportation sector by 2045. The team is focused on three main tasks to support development of convenient mobility options:

1. Develop a shared transportation mobility data plan to collect information on movement patterns of both residents and visitors and assess detailed transportation demand around the Island;
2. Analyze and plan the role of emerging mobility technologies in conjunction with Kaua‘i's existing transit plans to support a broader array of transportation choices for visitors and residents on the island; and
3. Devise plans for electric vehicle charging infrastructure to improve the mobility and accessibility needs of residents and visitors on the island and expand charging access for those who are not willing, able, or prepared to shift away from single occupancy vehicles at this time.

Funding Source: U.S. Department of Energy

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Last Updated: November 2021

B1: 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 that allows tighter, localized coordination of distributed energy resources (DERs), such as rooftop solar photovoltaics (PV). This is important for Hawaiʻi because as power generation and ancillary services become more decentralized, there is a need for enhanced measurement, data analytics, and controls near the grid edge. Field devices, such as advanced meters, line sensors, and secondary reactive power (var) controllers are all part of the grid modernization strategy of the local Hawaiʻi utility, and many utilities abroad. 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 for real-time data analysis–all in a small weather resistant enclosure.

Project Status/Results: ARGEMS devices have been successfully deployed at UH Mānoa, 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.

Figure 1. ARGEMS devices prior to shipment.

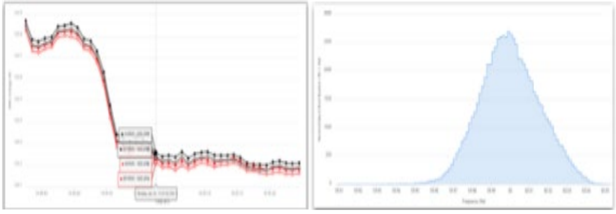

Figure 2. Analysis and visualization of real-time data.

A U.S. patent (#11,146,103) for the system was awarded to the University of Hawaiʻi in October 2021. Discussions regarding potential use cases and demonstrations have been initiated with utilities in Hawaiʻi, Alaska, and Thailand. The software stack is now well-documented and tested. Onboard power flow simulation capabilities have been established. Printed circuit board (PCB) design is well-refined. Commercial assembly indicated that costs are competitive with traditional distribution service transformer monitors.

The project has enabled and fostered new collaborations, funded research, and outreach. Research has included distributed volt/var control, optimal electric vehicle scheduling and charging, and novel methods of fault location. Fourteen undergraduate students and eight international interns have been involved in the project. The system has also been presented and shared through ThinkTech Hawaiʻi, SOEST's Open House, UH Sea Grant's Voices of the Sea, IEEE Power and Energy Society, and Engineers and Architects of Hawaiʻi.

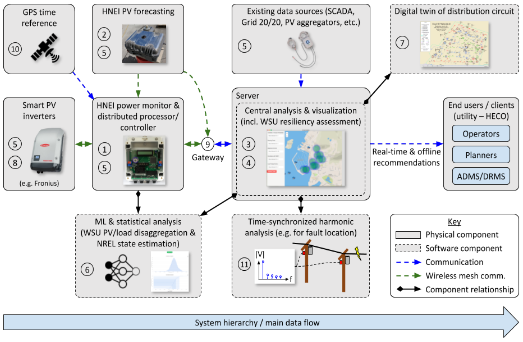

Figure 3. Application to real-time analytics and controls.

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

Contact: Kevin Davies, kdavies@hawaii.edu

Last Updated: November 2021

B2: Solar Power Forecasting

Objective and Significance: This project's objective is to develop advanced forecasting systems, including new methods and technologies, to predict solar photovoltaic (PV) power generation from minutes to days ahead. Knowledge of upcoming PV power production allows grid operators and grid management systems to proactively address the inherent variability of solar power. These systems also provide visibility and situational awareness for distributed behind-the-meter solar systems, helping to minimize the impact of reliability issues and disruptive events and manage the cost of grid operations, as the levels of PV interconnected to the electric grid increase.

Background: Power output from PV systems is directly related to the power of the sunlight striking the panel, measured as irradiance. Irradiance variability at the top of the atmosphere (TOA) is driven by sun-earth geometry and fluctuations in solar output that occur on nearly periodic 11 year solar cycle. TOA irradiance varies predictably at diurnal, seasonal, and interannual time-scales. As solar radiation passes through the atmosphere, it is attenuated through a complex series of reflections, absorptions, and re-emissions due to interactions with clouds, fog, and haze, as well as other particulates, such as dust, ash, and smog. Ground-level irradiance varies erratically across a range of time-scales. A sample day of irradiance observations and measurements of PV output from the University of Hawaiʻi (UH) FROG Building is shown in Figure 1.

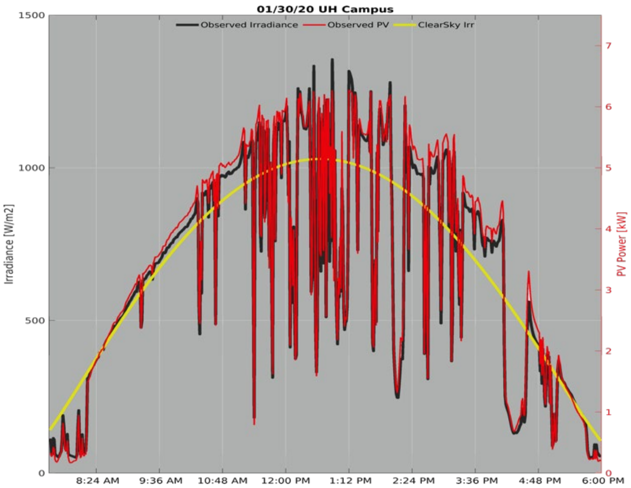

Figure 1. Irradiance observations and PV power measurements from the UH FROG Building on January 30, 2020.

HNEI developed a multi-scale, probabilistic solar forecasting system that monitors current regional irradiance conditions in near real-time and predicts upcoming irradiance conditions and resulting PV power production, from minutes up to 4-days ahead. This system is fully automated, generating predictions without human intervention.

Probabilistic irradiance predictions are generated using ensemble methods that combine individual, overlapping forecasts from three components. Each component focuses on, and is more accurate at, a different forecasting horizon. The ensemble methodology increases forecasting accuracy and allows for spatial and temporal flexibility in PV production forecasts.

Minute-ahead (MA) forecasts, from 1 to 30 minutes ahead, are provided by the Affordable High-Resolution Irradiance Prediction System (AHRIPS), a novel solar forecasting instrument developed by HNEI's Grid***START*** team. MA forecasts contain valuable information on the timing and magnitude of upcoming PV ramp events. A sample AHRIPS sky-image is shown in Figure 2.

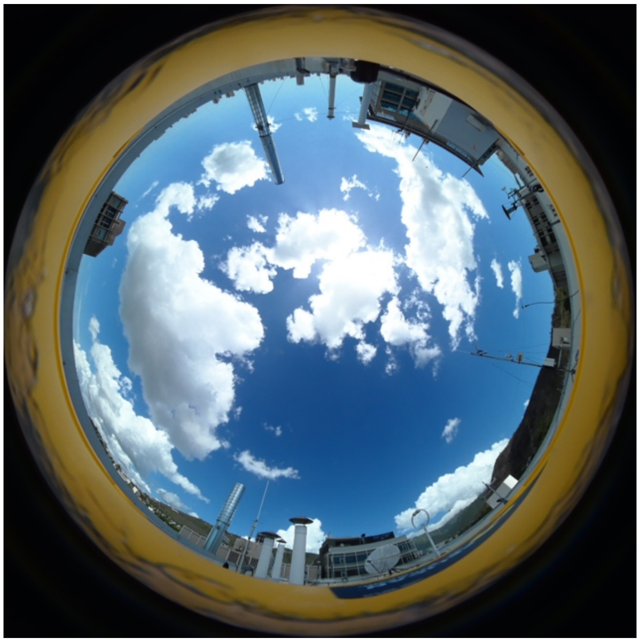

Figure 2. AHRIPS sky image taken from the UH Mānoa campus on October 25, 2020.

Hour-ahead (HA) forecasts, from 10 minutes to 6 hours ahead, are derived from geostationary satellite images, which provide consistent monitoring of regional atmospheric conditions. HA forecasts provide information to support unit dispatch and operational reserve management. A sample irradiance "nowcast" map from GOES-17 is shown in Figure 3.

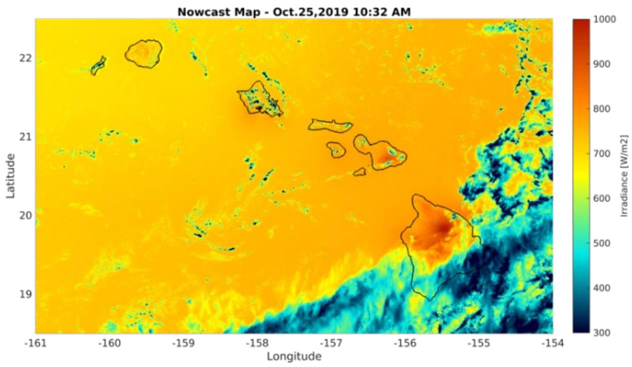

Figure 3. Sample irradiance nowcast map derived from GOES-17 imagery.

Day-ahead (DA) forecasts, longer than 6 hours ahead, are generated using a specific configuration and augmentation of the Weather Research and Forecasting (WRF) system designed for solar energy applications. WRF is a next-generation mesoscale numerical weather prediction system provided by the National Center for Atmospheric Research (NCAR). DA forecasts provide information to support utility generation unit planning and scheduling.

<u>PROJECT STATUS/RESULTS</u>: The HNEI solar forecasting system was originally developed for the Hawaiian Islands, but its design incorporates a flexible platform that allows for component updates and regional flexibility. Other applications have included: a South Korea domain, for operational forecasting of PV systems at the Korea Electrotechnology Research Institute campus in Changwon, South Korea; a Thailand domain, for a feasability study that focused on northern Thailand; a SE United States domain, for a feasability study that focused on the state of Georgia; and a Puerto Rico Domain, for a feasability study that focused on the island of Puerto.

The system is currently generating operational forecasts for a Hawaiian Island domain that includes all of the main islands of the Hawaiian archipelago. Multiple probibalistic irradiance and PV power forecasts are generated from ensembles composed of 4-day ahead WRF forecasts, generated nightly, and 6-hour ahead GOES forecasts, generated from the latest satellite images, every 5-10 minutes.

Realtime forecasts are shown along with realtime observations at: http://128.171.156.27:5100/uhfrog/ and http://128.171.156.27:5100/hawaii/. Figure 4 shows a sample probabilistic forecast from September 25, 2020 at 12:22 PM HST for the Natural Energy Laboratory of Hawaiʻi Authority (NELHA) technology park on the Island of Hawaiʻi.

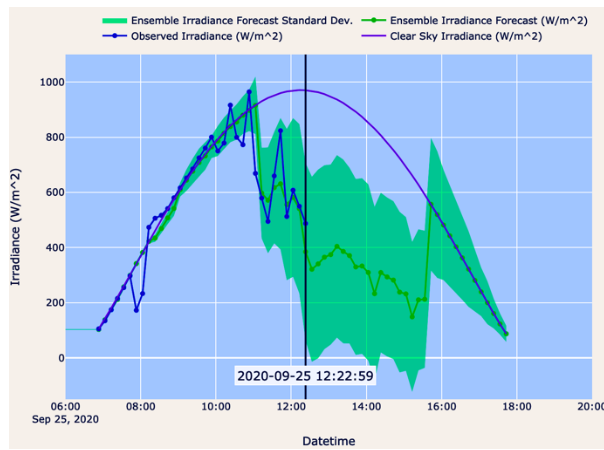

Figure 4. Sample output from the forecasting system. The probabilistic forecast (green), while realtime observations (blue). The black solid line indicates the current time.

In April, 2021 a patent for the AHRIPS hardware and software was approved by the U.S. Patent & Trademark Office: Matthews, Dax Kristopher, 2021, Ground-based sky imaging and irradiance prediction system, U.S. Patent 10989839, filed August 29, 2018, and issued April 27, 2021.

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

Contact: Dax Matthews, daxm@hawaii.edu

Last Updated: November 2021

Appendix B: Grid Technology Development

B3: Coconut Island DC Microgrid

OBJECTIVE AND SIGNIFICANCE: HNEI is developing a DC-based microgrid on Coconut Island (Figure 1), home to the University of Hawaiʻi's Hawaiʻi Institute of Marine Biology (HIMB), located in Kāneʻohe Bay, Oʻahu. The project objective is to demonstrate and assess the reliability, resilience, and energy efficiency benefits of a DC microgrid serving two HIMB buildings. The system is intended to support critical building loads during grid supply interruptions and provide clean transportation options powered primarily by rooftop solar energy. The project results and lessons can be applied in future DC-based microgrids in Hawaiʻi and abroad.

Figure 1. DC microgrid project site, Coconut Island.

BACKGROUND: Among HIMB's goals is for the island and its research facilities to serve as a model for sustainable systems. Thus, it is an ideal site for a renewable energy technology-based microgrid test bed that represents a remote location vulnerable to energy disruption, yet serving mission critical power needs. Key project goals include: 1) adoption of innovative energy efficient and reliable clean energy technologies; 2) establishment of a research platform to study resilient DC microgrid technologies (e.g., microgrid controller, energy storage, DC powered appliances, etc.) in a tropical coastal environment; and 3) development of solar powered DC all-electric land (E-car) and sea (E-boat) transportation solutions.

International partnerships with the Okinawa Institute of Science and Technology (OIST), Japan, PUES Corporation (PUES), Japan, and University of Indonesia (UI), Indonesia are central to this project. A DC-powered e-car, e-boat (Figure 2), and portable emergency power source using a novel swappable battery energy storage system were co-developed with OIST and PUES. The swappable batteries used in these e-mobility solutions are supplied primarily by energy from a new 6.2 kW rooftop solar PV system coupled with an 8 kWh battery energy storage system (BESS). These energy resources, along with minimal grid power, also supply DC lighting, DC air conditioning, and building critical loads within the microgrid.

Figure 2. Collaborative e-boat and e-car development.

The partnership with UI has yielded a new version of a UI designed DC-DC converter (DCON) (Figure 3), which transforms the voltage of the PV and BESS 48 V DC bus to the 200-350 volts required by the various DC microgrid loads. The DCONs deployed and under test in this project are a significant advancement of predecessor technology earlier deployed in a UI sited DC microgrid.

Figure 3. University of Indonesia DCON devices.

PROJECT STATUS/RESULTS: The e-boat and e-car solutions are operational and under test and evaluation by HNEI's Grid***START*** team. The 6.2 kW rooftop solar PV system and 8 kWh BESS are now installed and fully commissioned. While COVID-19 restrictions on project site-based work impacted progress from early 2020 through much of 2021, the remaining primary microgrid elements, including custom microgrid controls, electrical equipment such as the DCONs, switches, protection, metering, wiring, and all DC loads, are currently being installed and commissioned. Full DC microgrid operation is anticipated in Q1 2022.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

B4: NELHA HOST Park Microgrid Analysis

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to determine the feasibility and benefits of modifying the current energy system at Natural Energy Laboratory of Hawaiʻi Authority (NELHA)'s Hawaiʻi Ocean Science and Technology (HOST) Park to enable it to operate as a microgrid (or a number of microgrids) connected to the Hawaiʻi 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.

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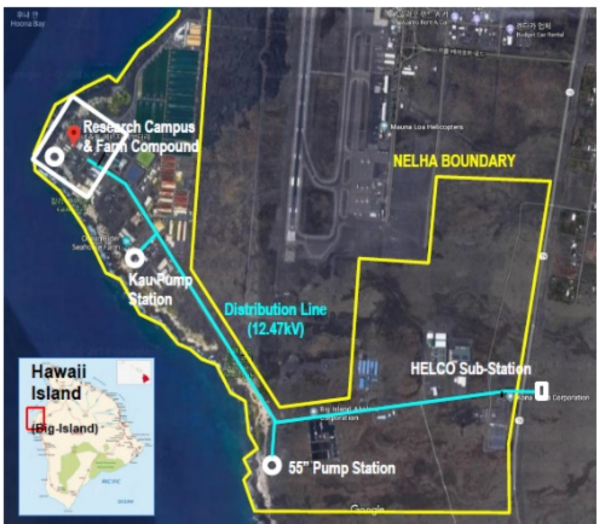

Figure 1. NELHA's HOST Park site and existing HELCO primary distribution feeder.

BACKGROUND: Microgrids, especially those integrating renewable energy resources, are of interest in Hawaiʻi for their potential to enhance the reliability of the microgrid site and host grid, increase energy assurance, improve security, and potentially reduce cost and carbon footprint. Microgrids can also improve resilience against both manmade and natural disruptions. Act 200 of 2018 directed the Hawaiʻi Public Utilities Commission (PUC) to open a proceeding to establish a microgrid services tariff to encourage and facilitate 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 has identified regulatory and policy issues currently in place that hinder the development of microgrids and offer modifications to those regulations and policies for future action.

PROJECT STATUS/RESULTS: In collaboration with NELHA staff, have completed three tasks and delivered three reports to NELHA. In Task 3.1 and its report, a power system requirements analysis of the HOST Park based on NELHA's energy projections for a ten-year period was conducted, identifying the current and projected future power system requirements of the 870-acre HOST Park. In Task 3.2 and its report, both the technical and regulatory/policy opportunities and barriers, with potential on-site distributed generation, energy storage, power management, and control technology alternatives, were evaluated, and the most promising ones that could be applied at the HOST Park were identified. In Task 3.3 and its report, HNEI developed microgrid power system conceptual design options that meet the HOST Park's power requirements, based on the results of Tasks 3.1 and 3.2, considering current grid, regulatory and policy constraints, as well as designs based on reasoned relaxing of such constraints within the HOST Park boundaries.

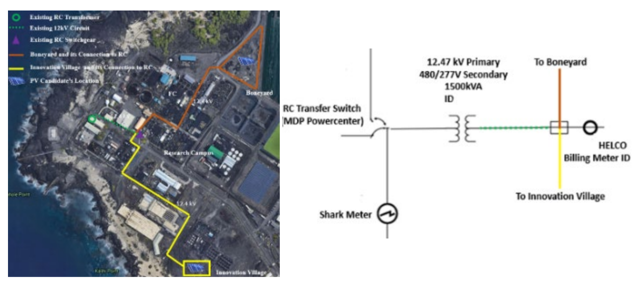

Figure 2. Example of the microgrid power system conceptual design options.

A final report from HNEI providing a roadmap for NELHA to efficiently and effectively realize its microgrid aspirations over a ten-year planning horizon is planned to be issued in November 2021.

Funding Source: Hawaiʻi State Energy Office via NELHA

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

B5: Advanced Conservation Voltage Reduction Development & Demonstration

<u>Objective and Significance</u>: The objective of this project is to demonstrate conservation voltage reduction (CVR) as an effective way to conserve 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.

<u>Background</u>: The primary value proposition of CVR implementation is the 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 were identified for CVR field test and evaluation.

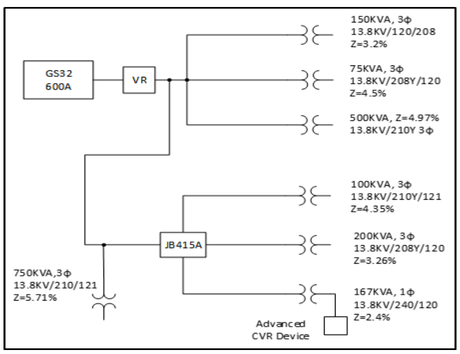

Figure 1. CVR Demonstration Single-Line Diagram.

The CVR controlled feeder section is isolated with a new voltage regulator (VR) to control the voltage at “downstream” service transformers, 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.

<u>Project Status/Results</u>: Utilizing HNEI’s hardware-in-the-loop (HIL) laboratory platform, testing and validation of the CVR control algorithm, including communication between the controller and field meters to be located at service transformers were completed.

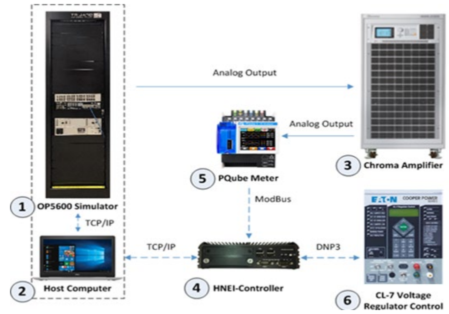

Figure 2. CVR real-time HIL test set-up.

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.

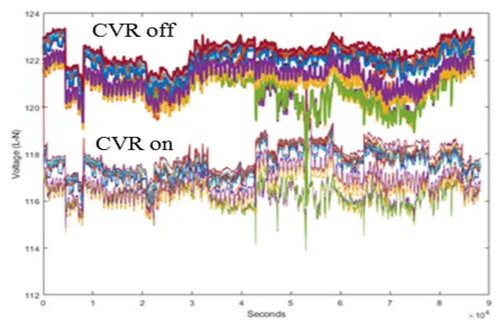

Figure 3. Voltage Profiles with CVR on and off.

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, delayed due to COVID-19 travel restrictions to Japan, is planned in January 2022.

Figure 4. Project construction and new PV system.

Funding Source: UH ARL; Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

B6: Energy Generation and Resilience Opportunities Assessment for MCBH

OBJECTIVE AND SIGNIFICANCE: HNEI is conducting an assessment of energy generation and resilience opportunities ("EG&R Assessment") for Marine Corps Base Hawaiʻi (MCBH). This study seeks to identify and evaluate needs and opportunities for implementing cost-effective and commercially proven microgrid technologies (e.g., solar photovoltaics (PV), battery energy storage systems (BESS) and back-up diesel generation) on MCBH, while concurrently meeting MCBH's 14-day resiliency requirement.

Figure 1. Marine Corps Base Hawaiʻi at Kāneʻohe 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 Installation Energy and Security Plan (IESP) be prepared for MCBH. HNEI was initially assisting MCBH with the development and completion of MCBH's IESP and delivered a preliminary draft of the report in October 2020.

Earlier in 2020, the Marine Corps Installations Command (MCICOM) took over efforts to complete IESPs for all installations under its umbrella. As MCBH was still interested in HNEI's assistance to identify base energy security gaps and evaluate alternative energy resilience solutions, the scope of work of HNEI's analysis was updated and the EG&R Assessment was initiated.

PROJECT STATUS/RESULTS: Having completed a preliminary analysis of the existing MCBH electrical infrastructure and loads in 2020, HNEI recently completed a techno-economic analyses utilizing the commercial microgrid assessment software, XENDEE Microgrid Decision Support Platform ("XENDEE"), evaluating optimized long-term hybrid microgrid solutions incorporating both existing and new on-base PV generation, BESS resources and back-up diesel generation.

Alternative microgrid designs have been proposed, developed and assessed, including microgrid solutions that range from powering the entire base, to smaller footprint microgrids that maintain power to each of the several base primary substations. Additionally, HNEI has analyzed the feasibility of microgrids at a more granular distribution feeder level, including at the request of MCBH leadership, an assessment of the potential for microgrid development cost reduction opportunities by the use of existing rooftop PV systems and emergency generation assets already in place at critical load centers on the base.

Figure 2 illustrates a conceptual microgrid design that utilizes existing rooftop PV at MCBH and proposes additional generation and energy storage resources to power the entire base in the event of an extended utility service outage.

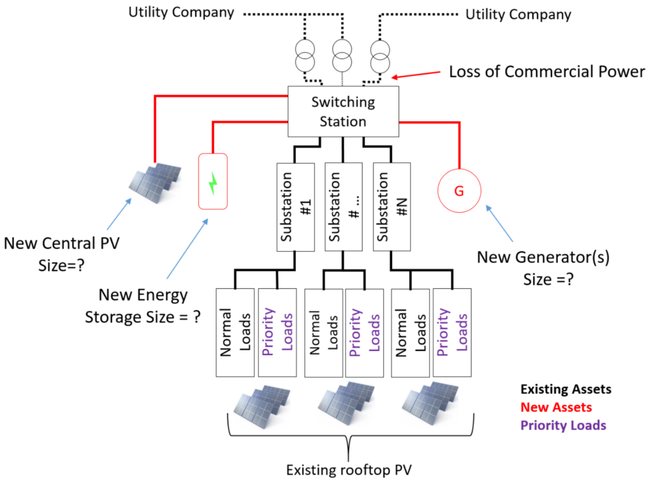

Figure 2. Conceptual design of a full-base microgrid.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

B7: Hawaiʻi Virtual Power Plant (Hi-VPP) Demonstration

OBJECTIVE AND SIGNIFICANCE: The objective of HNEI's Hawaiʻi Virtual Power Plant Demonstration Project (Hi-VPP) is to quantify the economic value and operational effectiveness of battery and solar (BESS+PV) resources to simultaneously provide customer and grid-side services when aggregated as part of a virtual power plant (VPP). This project is expected to provide key insights into the economic synergy and optimization of multiple services under BESS control, as well as the functional tradeoffs between simple, low-bandwidth and advanced, highly-coordinated methods of VPP aggregation. Ultimately, it will help better quantify the business case for VPPs, including the value proposition for customer participation in a VPP and utility utilization of the same.

BACKGROUND: At the completion of the JUMPSmart Maui (JSM) smart grid project funded by the New Energy and Industrial Technology Development Organization (NEDO) of Japan, HNEI negotiated and executed an Equipment Transfer Agreement with NEDO resulting in HNEI acquiring significant grid assets deployed in the JSM project. HNEI's Grid***START*** team has leveraged the acquisition of the Sunverge Solar Integration System (SIS) BESS + PV units installed at Haleakala Solar's business office to conduct this project, with a goal of demonstrating and assessing the technology application and the value proposition/prioritization of alternative use cases based on stakeholder interests and functional/ economic trade-offs.

Figure 1. Sunverge Solar Integration System (SIS) BESS + PV units.

PROJECT STATUS/RESULTS: A new electrical service was installed to connect the SIS BESS units at the Haleakala Solar location to the power system of the local utility, Maui Electric Company, Ltd. (MECO). End-user loads at the host location were also transferred to the new service. After a series of maintenance and repair efforts, four of the BESS+PV units are online, operational, and approved for operation by MECO.

Identifying that the system required new sensors to measure behind-the-meter (BTM) loads, HNEI built and is currently contracting the installation of a load measurement box based on four Advanced Real-Time Grid Energy Monitor System (ARGEMS) devices.

Figure 2. Load measurement box.

Significant progress had been made in the formulation, implementation, and control application of the underlying economic optimization. The Grid***START*** team began by investigating relevant grid services and value streams for the Hawaiʻi market, discussing the application with Sunverge representatives, and formulating a baseline optimization problem. Programming and configuration of the optimal controls, including the solver and plant communications, is well underway.

$$\max \sum \underset{\text{(Solar + Storage)}}{Value\ of\ BTM\ DER\ Assets} =$$

1. *Customer Side Benefits*
   i. **Consumer Bill Savings**
   ii. **Backup Power**
2. *Grid Side Benefits*
   a. Distribution Level
      i. **Peak Power Reduction**
   b. Bulk Level
      i. **Dispatchable Firm Capacity**
      ii. **Bulk Power Energy Shifting**
      iii. **PV Firming Through End-of-day Ramping Control**
      iv. **Replacement Reserves**

Figure 3. Summary of value streams and optimization.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

C1: Sustainable Aviation Fuel Production

OBJECTIVE AND SIGNIFICANCE: Commercial aviation in Hawaiʻi currently uses nearly 700 million gallons of jet fuel per year, all of it is derived from petroleum. The University of Hawaiʻi (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 alternative, renewable, sustainable, jet fuel production in Hawaiʻi. Results may inform similar efforts in other tropical regions.

BACKGROUND: This project was initiated in October 2015 and is now continuing into its 6th 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 Hawaiʻi;
- Developing fundamental property data on biomass resources; and
- Developing and evaluating regional supply chain scenarios for SAF production in Hawaiʻi.

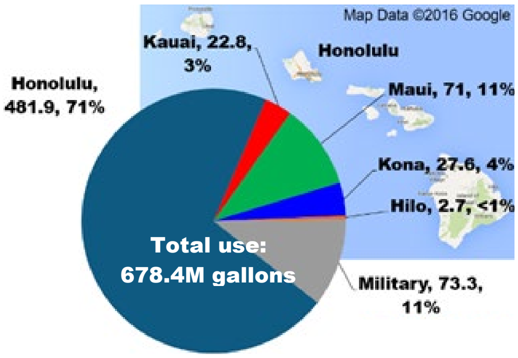

Figure 1. Commercial and military jet fuel use in 2015.

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 Hawaiʻi 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.

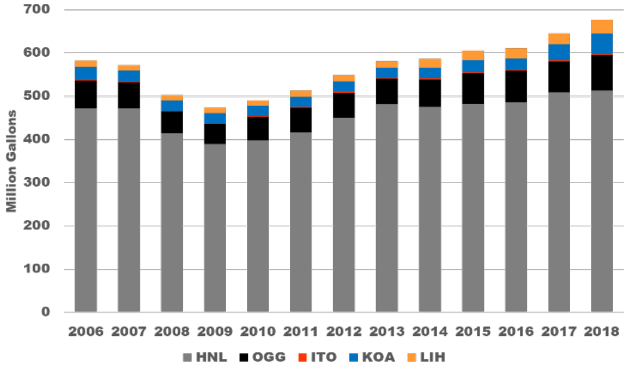

Figure 2. Commercial jet fuel consumption in Hawaiʻi.

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 Oʻahu. Complete results will be summarized in a forthcoming journal article. As shown in Figures 3 and 4, although the combustible fraction of the samples have elevated ash levels compared to clean biomass materials, their heating values were comparable, indicating the presence of higher energy density materials. As with most refuse derived fuels, the amount of ash in the fuel and its composition is of particular importance, since ash impacts energy facility operations, maintenance, and emissions.

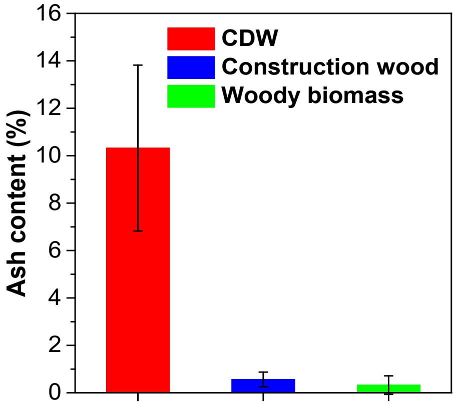

Figure 3. Ash content of the combustible fraction of CDW compared to construction wood and woody biomass.

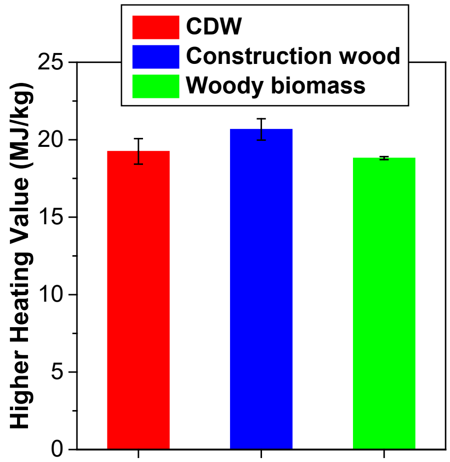

Figure 4. Heating value of the combustible fraction of CDW compared to construction wood and woody biomass.

Future work with ASCENT partners includes:

- Analysis of feedstock-conversion pathway efficiency, product slate (including co-products), maturation;
- Scoping of techno-economic analysis (TEA) issues;
- Screening level greenhouse gas (GHG) life cycle assessment (LCA);
- 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 5 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, which 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; an example is shown for a eucalyptus species on the following page (Figure 6). Ongoing work will identify underutilized agricultural areas and supply chain components necessary to develop SAF production systems.

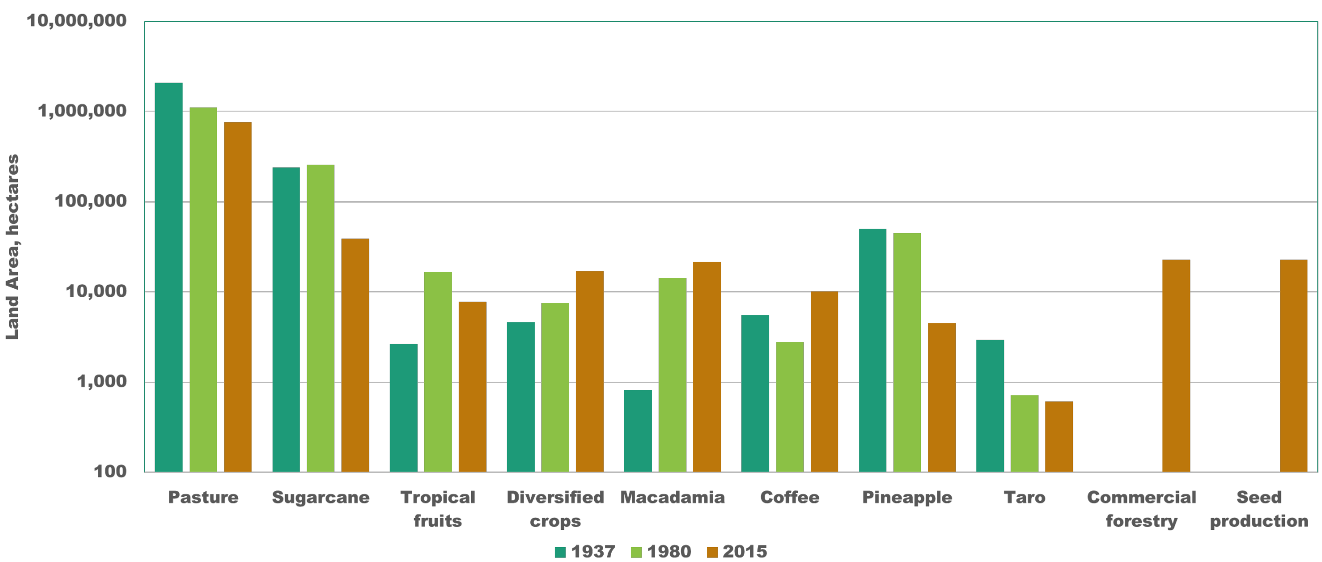

Figure 5. Breakdown of agricultural land use in Hawai‘i; in 2015, approximately 100,000 acres were harvested.

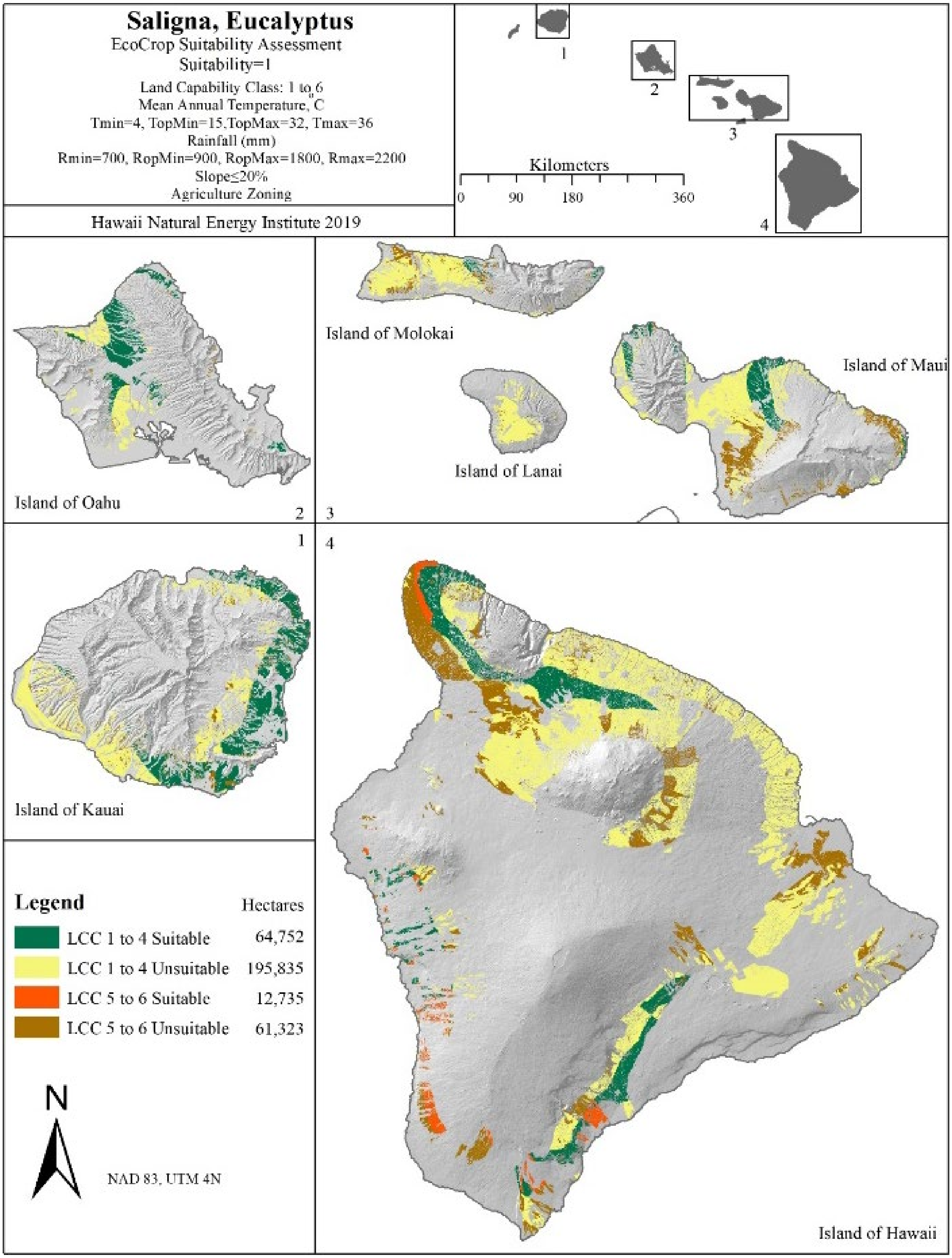

Figure 6. EcoCrop assessment of Saligna, Eucalyptus.

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.

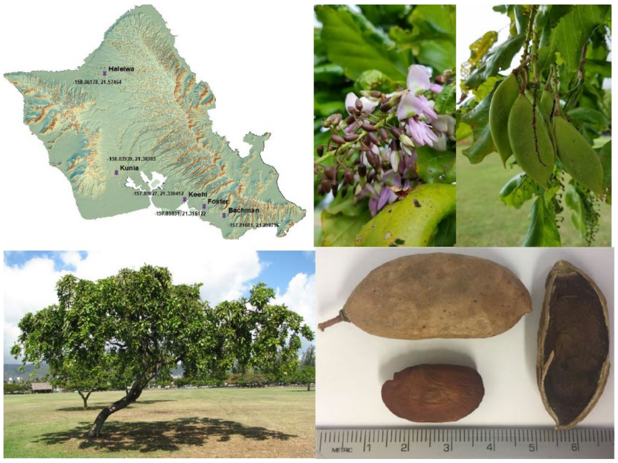

Figure 7. Locations and images of Pongamia.

Invasiveness Assessment

Pongamia (*Milletia pinnata*) is a tree, native to the tropics, that bears an oil seed and has plantings established on O‘ahu. 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 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. This physicochemical properties of reproductive material (seeds and pods) from pongamia trees grown in different environments at five locations on O‘ahu were characterized. 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 aviation fuel.

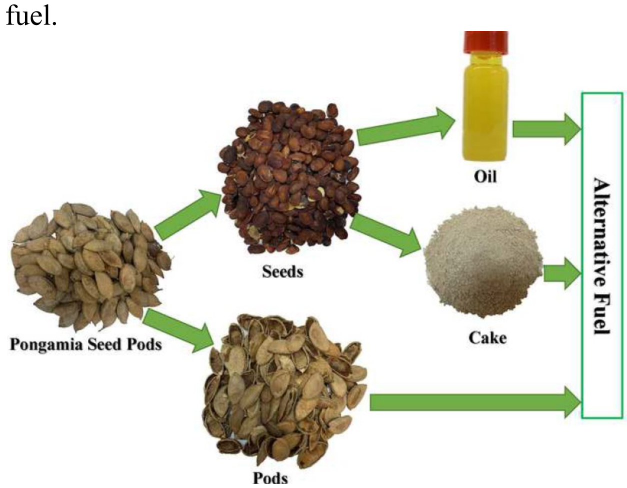

Figure 8. Pathways from Pongamia seed pods to fuel.

Coproduct Development

Additional studies were devoted to developing coproducts from pongamia pods. Leaching and torrefaction experiments were performed to remove inorganic constituents and reduce the oxygen content of the pods. A 2^3 factorial design of the leaching treatment determined the impacts of process operating parameters (i.e. rinse water temperature, rinse duration, and particle size) on the composition and physicochemical properties of the pods and the water. The higher heating value of the pods was found to increase from 16 to 18-19 MJ/kg after leaching, while the ash content was reduced from 6.5% to as low as 2.8%wt, with significant removal of sulfur (S), chlorine (Cl), and potassium (K). The chemical oxygen demand, non-purgeable organic carbon, and total nitrogen of the post-experiment leachates were all found to increase with the rinse water temperature and rinse duration but decrease with the increase of particle size. Leached pods were further processed via torrefaction and the targeted mass and energy yields, ~70% and 85%, respectively, were reached at a process temperature of 270°C. The S, Cl, and K contents of the leached, torrefied pods were found to be lower than that of the raw pods. The reuse of leachate on successive batches of fresh pods showed that ash removal efficiency was reduced after three cycles, although some removal was possible through 15 cycles.

Figure 9. Laboratory scale leaching and torrefaction test equipment.

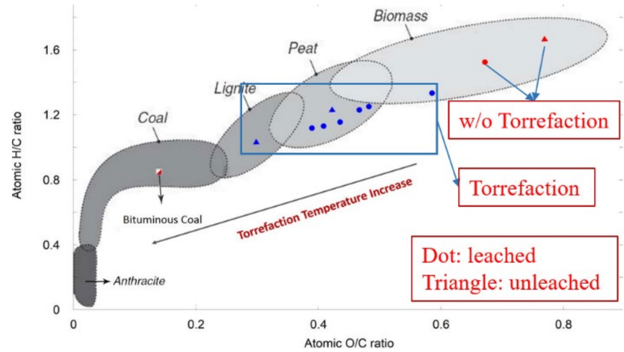

Figure 10. Van Krevelen diagram.

Other Feedstocks
Other potential feedstocks for Hawai'i, kukui (*Aleurites moluccanus*) and kamani (*Calophyllum inophyllum*) nut oils, were also explored. Preliminary studies found the oil content of the kukui nuts is ~60% wt, which is ~20-30% wt higher than that of pongamia seeds and kamani nuts. The unsaturated fatty acids, however, accounted for ~90 % wt of the kukui nut oil, slightly higher than that of kamani nut (~75% wt) and pongamia seed oil. Kukui and kamani nut oil are different from the pongamia seed oil, in that the primary fatty acid is linoleic acid (C18:2).

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

Contact: Scott Turn, sturn@hawaii.edu

Last Updated: November 2021

C2: Resources for Renewable Natural Gas Production in Hawaiʻi

OBJECTIVE AND SIGNIFICANCE: The purpose of this work was to 1) assess resources for renewable natural gas production in Hawaiʻi and 2) compare their potential for renewable natural gas (RNG) production to current levels of fossil derived gas consumption in the State.

BACKGROUND: In 2008, the Hawaiʻi Clean Energy Initiative began a concerted effort to move Hawaiʻi toward a renewable energy future. While early focus has been on electricity from solar and wind, an interest in making use of biorenewable resources has been an ongoing theme across energy sectors, driven by renewable portfolio standards and a commitment to forego new fossil generating assets. This interest is demonstrated by the state legislative and executive branches, county governments, regulated and unregulated energy providers, community stakeholders, and consumers.

RNG is composed primarily of methane derived from carbon of recent biogenic origin, unlike fossil natural gas (NG) that derives from ancient carbon commonly associated with fuels, such as coal or petroleum. Either of these latter two resources can be used to produce synthetic natural gas (SNG) by thermochemical energy conversion methods. In general, RNG has lower life cycle greenhouse gas (GHG) emissions than NG. Depending on resource (feedstock) and production method, net GHG emissions for RNG can range from -50 to 7 kg CO_{2eq} / therm (-480 to 66 g CO_{2eq}/MJ)[6,7]. NG has net GHG emissions of about 7.4 kg CO_{2eq} / therm (70.1 g CO_{2eq}/MJ)[6]. The production of RNG makes use of biological or thermochemical conversion processes. Both are described in more detail below. Existing sources of biogenic methane in Hawaiʻi that could be used to produce RNG are explored. Biomass resources that are used as the carbon feedstock for RNG production are also discussed and their occurrence in Hawaiʻi reviewed.

RNG has the potential to directly displace incumbent fossil energy products (substitution) or to be part of a retrofit or new equipment package that would displace both the fossil fuel and end-use conversion technology. An example of the former is substitution of RNG for fossil gas use in process heat applications, whereas an example of the latter is a diesel engine replaced with an engine fueled by compressed RNG.

To provide context for the report, Hawaiʻi consumption of fossil energy products with potential for displacement by RNG were reviewed. Data from the U.S. Energy Information Agency (EIA)[8] for 2018, the most recent year with complete reporting, are presented below. Three EIA categories of fossil energy products were identified:

1) natural gas excluding supplemental gas fuels – includes 0.2 trillion Btu (2 million therms, 211 TJ) of imported liquefied natural gas (LNG);
2) natural gas including supplemental gas fuels – includes the LNG from (1) above and synthetic natural gas (SNG) produced from petroleum naptha feedstock, and totals 3.2 trillion Btu (32 million therms, 3.4 PJ); and
3) hydrocarbon gas liquids – includes natural gas liquids and refinery olefins totaling 3.7 trillion Btu (37 million therms, 3.9 PJ).

EIA assumes that hydrocarbon gas liquid (category (3) above) consumed in the residential, commercial, and transportation sectors is propane[9]. In practice, this fraction of the hydrocarbon gas liquid stream is liquefied petroleum gas (LPG), a mixture containing ~90% propane with the balance primarily butane and ethane. Combined, the three sector consumption of LPG totaled 3.3 trillion Btu (33 million therms, 3.5

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[6] California Air Resources Board, Low Carbon Fuel Standard Pathway Certified Carbon Intensities, Accessed April 2021. https://ww2.arb.ca.gov/resources/documents/lcfs-pathway-certified-carbon-intensities

[7] 2019, R. Serra, et al., From conventional to renewable natural gas : can we expect GHG savings in the near term?, Biomass and Bioenergy, Vol. 131, Paper 105396. http://dx.doi.org/10.1016/j.biombioe.2019.105396

[8] U.S. Energy Information Administration, 2020, State energy data system (SEDS): 1960-2018 (complete): Hawaiʻi State profile and energy estimates – Primary energy consumption. https://www.eia.gov/state/seds/seds-data-complete.php?sid=HI#Consumption

[9] U.S. Energy Information Administration, 2019, State profiles and energy estimates: Technical notes & documentation – updates for 2019; Section 4: Petroleum. https://www.eia.gov/state/seds/sep_fuel/notes/use_petrol.pdf

PJ) in 2018[10]. These data indicate that 2018 LNG and SNG consumption was on equal footing with LPG use on an energy basis.

LNG, SNG, and a fraction of the LPG used in the state are delivered to consumers by Hawai‘i Gas' underground pipelines. Those customers not served by pipelines receive LPG in bulk tanks of varying size. The method of delivery is the primary delineation between regulated (pipeline) and unregulated (bulk) gas sales[11].

EIA totals can be compared with locally available data. The following is excerpted from the Annual Renewable Energy Report filed by Hawai‘i Gas in accordance with HRS 269-45, Gas Utility Companies Renewable Energy Report[12].

"*Hawai‘i Gas' utility gas operations consist of the purchase, production, transmission, distribution, and sale of utility gas, which includes synthetic natural gas [SNG], renewable natural gas [RNG], propane, and liquefied natural gas [LNG], which are clean-burning fuels that produce significantly lower levels of carbon emissions than other hydrocarbon fuels, such as oil and coal. Hawai‘i Gas provides a safe, reliable, and economical source of energy to approximately 70,000 residential and commercial customers throughout the State, with almost half of those customers served by the utility system on O‘ahu.*

SNG is produced using naphtha, a byproduct or waste of the existing oil refining process in Hawai‘i, steam, water and hydrogen [in large part from recycled wastewater]."[12]

Hawai‘i Gas reports that commercial customers (10% of their base) consume 85% of the gas and residential customers account for the balance[13].

Hawai‘i Gas' Annual Renewable Energy Report[12] also includes the following information related to their 2019 production:

- 905,837 barrels of imported oil saved by using SNG instead of electricity;
- 5,446,140 Btu per barrel of oil; and
- For every 1 (one) barrel of therm equivalent SNG, it would require 2.813 barrels of oil for generator fuel.

Using this information and Equation (1), and noting that E2019 oil equivalent is 2.813 times greater than E2019, the energy content of Hawai‘i Gas' annual SNG sales from petroleum feedstock, E2019 was estimated at 27.2 million therms (2.87 PJ)[14]. This is comparable to the value of 32 million therms for "natural gas including supplemental gas fuels" reported by EIA[8].

$$E_{2019\,oil\,equivalent} - E_{2019} = E_{imported\,oil\,savings} \qquad (1)$$

Also providing context for the report, Hawai‘i Gas reports producing 381,529 therms (0.04 PJ) of RNG from biogas at the Honouliuli wastewater treatment plant (WWTP).

<u>Project Status/Results</u>: Feedstock resources for RNG production by biological (e.g. anaerobic digestion) and thermochemical (e.g. gasification) conversion methods in Hawai‘i have been reviewed. Estimates of resources for biological production (wastewater, landfills, food waste) have the potential to support 13.2 million therms per year (1,390 TJ y^{-1}, note that 1 therm = 100,000 Btu) of RNG production statewide (Table 1, on the following page). Similarly, estimates of the combustible portions of construction and demolition waste and municipal solid waste have the potential to generate 70.8 million therms per year (7,470 TJ y^{-1}) of RNG production statewide. Honolulu has the largest resource base for these urban waste streams. Underutilized agricultural land resources in the state could support substantial RNG

[10] U.S. Energy Information Administration, 2020, State energy data system (SEDS): 1960-2018 (complete): Hawai‘i State profile and energy estimates – Full reports & data files, all consumption estimates in Btu. https://www.eia.gov/state/seds/seds-data-complete.php?sid=HI#Consumption
[11] Department of Commerce and Consumer Affairs, State of Hawai‘i, 2021, Gas energy services. https://cca.hawaii.gov/dca/gas/
[12] Hawai‘i Gas 2019 Renewable Energy Report, Report to the Hawai‘i PUC in accordance with Hawaii Revised Statutes [HRS] § 269-45.
[13] Hawai‘i Gas website, Accessed in 2021. https://www.hawaiigas.com/
[14] U.S. customary units and International System (SI) units are included throughout the report, anticipating different preferences by prospective readership.

production from dedicated energy crops (~1,000 to 2,000 therms per acre per year (260 – 520 GJ ha-1 y^{-1})), although agronomic suitability of specific candidate energy crops would need to be evaluated and confirmed.

The estimates of potential RNG feedstock resources and RNG product provided in this report do not take into consideration factors including: economics, accessibility of a resource, availability of complementary factors of production, or the political, social, cultural, or regulatory environment. These factors would need to be considered in order to assess viability. Location of resources and access to infrastructure needed to implement successful RNG production, transmission, and distribution would necessarily depend on site-specific details, which are also not included in this report.

This work was completed in 2021 and the results of this study is available in the technical report: "**Resources for Renewable Natural Gas Production in Hawai'i**."

Funding Source: Energy Systems Development Special Fund

Contact: Scott Turn, sturn@hawaii.edu

Last Updated: November 2021

Table 1. Summary of RNG potential (million therms RNG/year) from resources in Hawai'i.

Resource Type	Maui	Kaua'i	Hawai'i	Honolulu	State Total
Livestock Manure	*	*	*	*	*
Wastewater Treatment Plants	–	0.02	0.06	1.8	1.9
Landfill Gas	2.2	1.0	0.6	2.5	6.2
Food Waste portion of MSW	1.8	0.5	2.3	0.5	5.1
Combustible portion of MSW	12.7	6.8	18.9	3.8†	42.3
CDW	-	-	-	28.5	28.5
Agricultural and Forestry Residues	‡	‡	‡	‡	‡
Energy Crops	§	§	§	§	§
Totals⸸	>17	>8	>22	>37	>84

* Insufficient number and size of animal feeding operations to justify methane production and recovery
† Estimated amount that is currently landfilled exclusive of HPOWER use.
‡ Insufficient available agricultural residues and ongoing forestry harvesting residues.
§ Underutilized agricultural land resources in the State could support substantial RNG production from dedicated energy crops (~1,000 to 2,000 therms per acre per year).
⸸ Totals would be larger with implementation of energy crop based RNG production.

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 and investigate the impacts of crucial nitrogen and sulfur containing compounds and additives on fuel properties. Comprehensive fuel composition information can be further employed to replace costly experimental measurements by calculating various physicochemical properties of fuel. The knowledge gained in this project will improve the understanding of the influences of HOS and fuel additive deterioration on fuel stability and physicochemical properties, guide efforts to preserve fuel quality, and reduce the cost of fuel characterization.

BACKGROUND: Liquid fuels are, by nature, chemically complex and many fit-for-purpose and stability issues are associated with trace quantities of HOS natural existed and additives employed. Identification and quantitation of HOS and additives 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, additives, 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 (≤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. Quantum chemical software based on the conductor-like screening model for realistic solvation (COSMO-RS) method was employed to calculate the physicochemical properties of petroleum and sustainable aviation fuels based on their individual 2D-GC compositions.

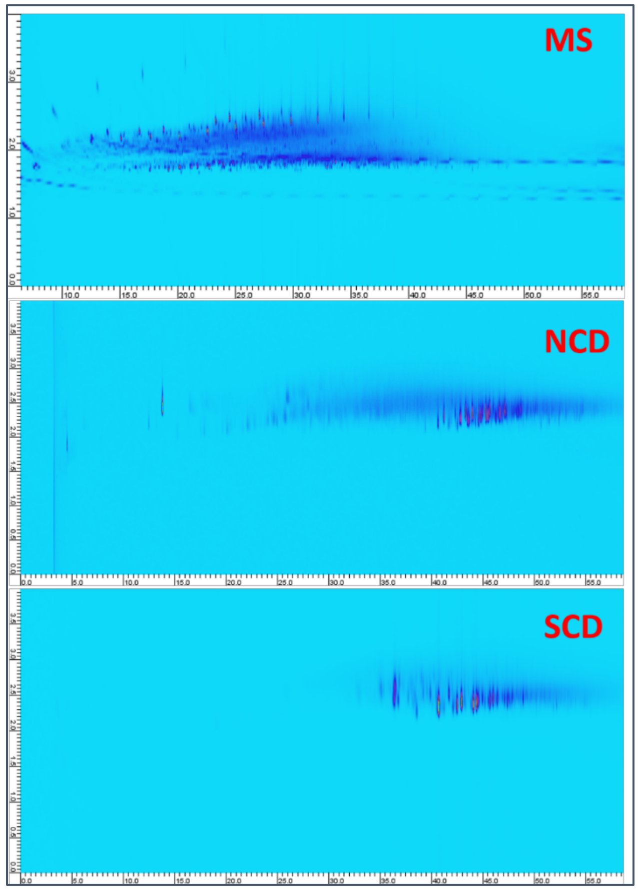

Figure 1. Comprehensive 2D-GC analysis of F-76 diesel fuel with MS, NCD, and SCD.

PROJECT STATUS/RESULTS: HNEI is currently collaborating with personnel from the U.S. Navy Fuels Cross-Functional Team at Naval Air Station Patuxent River (Pax River) and the Fuel Laboratory at Naval Supply System Command Fleet Logistic Center Pearl Harbor (NAVSUP FLC Pearl Harbor) on 2D-GC applications, including:

- Participated round robin tests on nitrogen compounds in various type of fuels;
- Predicted water solubility in fuels from -40°C to room temperature based on their individual 2D-GC compositions and COSMO-RS;
- Determining fuel hydrocarbon matrix;

- Investigating the distribution and contents of nitrogen and sulfur compounds in fuels;
- Incorporating novel separation methods to accurately qualify and quantify non-hindered and hindered phenolic species in fuel;
- Exploring the impacts of additive deterioration on fuel stabilities;
- Utilizing HOS characterization methods to investigate the potential impacts of HOS on fuel properties and fuel stability; and
- Calculating various fit-for-purpose properties based on the 2D-GC compositions of fuels.

Funding Source: Office of Naval Research

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Last Updated: November 2021

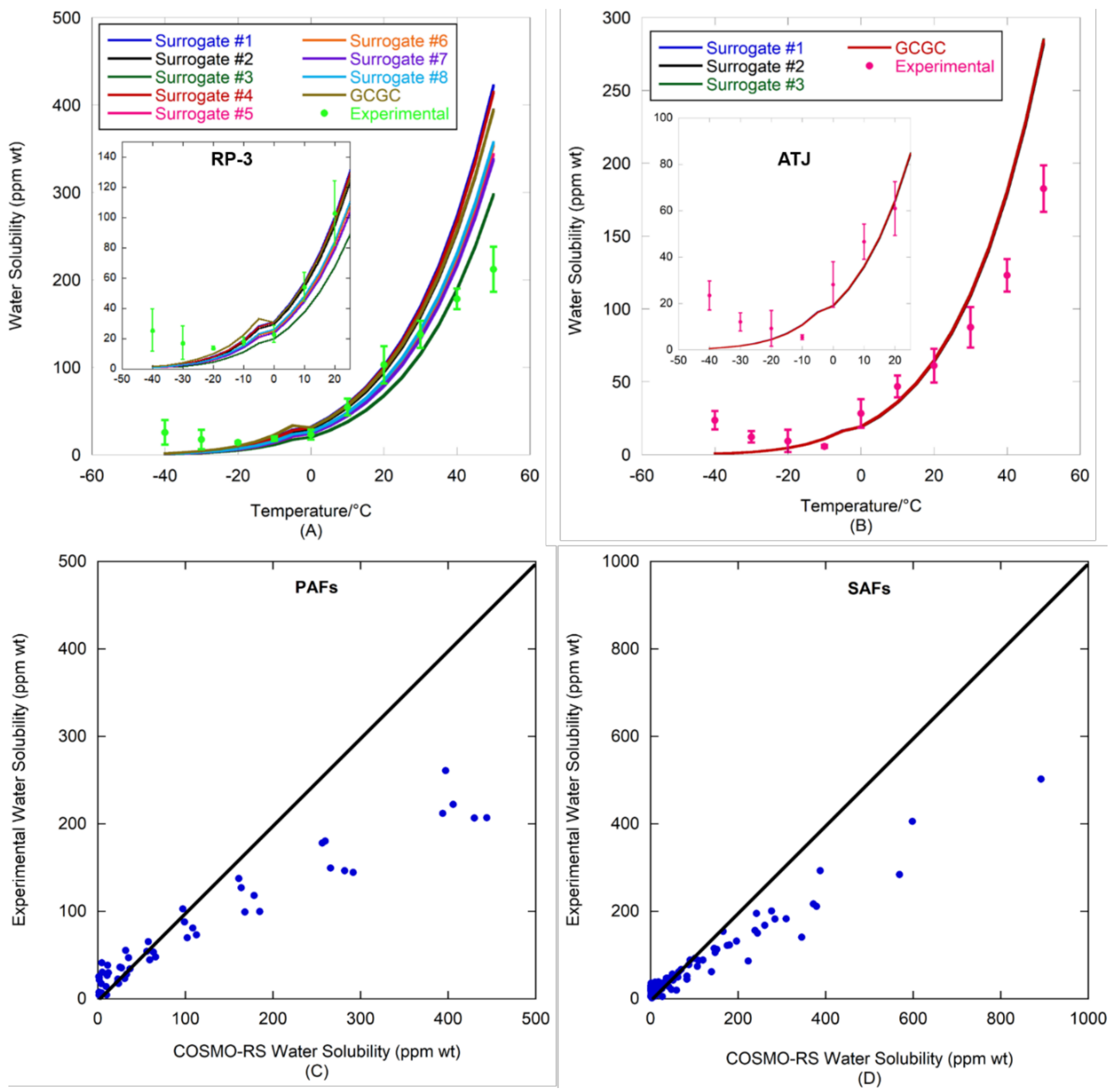


Figure 2. Correlation of COSMO-RS calculated water solubility in petroleum and sustainable aviation fuels (PAFs and SAFs) and their blends with experimental values reported by West et. al. 2018: (A)-(B) RP-3 and alcohol-to-jet with COSMO-RS calculation based on 2D-GC and surrogate data; (C)-(D) parity plots of 5 PAFs and 8 SAFs with COSMO-RS calculation based on 2D-GC data.

C4: Novel Biocarbons

OBJECTIVE AND SIGNIFICANCE: Biomass can be a renewable resource for the production of energy, fuels, chemicals, and materials. Most biomass materials have a carbon content of ~50% by weight. Slow pyrolysis is a thermochemical conversion process designed to produce a stable solid material with enriched carbon content and reduced amounts of oxygen. The intended end use of the solid carbonaceous material will dictate desirable properties (e.g. volatile matter, carbon and fixed carbon contents, reactivity, surface area, density, tensile/compressive strength, grindability, etc.). The solid product can be used as fuel for cooking, for water purification, as soil amendment, or as a coal replacement in industrial applications. Depending on end use and desired properties, the solid materials are referred to as charcoal, char, biochar, or biocarbons. All have uses in Hawai‘i and can be produced from lower or negative value biomass materials (wastes) as feedstock.

BACKGROUND: The production of biocarbons with high, fixed-carbon content has been an ongoing HNEI research effort. Exploring the conversion of biomass under constant-volume reactor conditions resulted in the production of biocarbons that exhibit characteristics consistent with having undergone a transient plastic phase (TPP) (Figure 1). Under less severe reactor conditions, the same biomass feedstock is converted to a powdered, free-flowing, biocarbon (Figure 2). Yields of these unique and novel biocarbons from constant volume pyrolysis and their fixed carbon contents have proven to exceed those previously reported in the literature using conventional carbonization methods and less developed techniques, such as hydrothermal carbonization. The current research effort uses an instrumented constant-volume reactor system to map reactor temperature and pressure conditions that result in TPP biocarbon formation. The TPP biocarbons are characterized to provide secondary maps of biocarbon properties. Characterization of these novel materials will provide the data necessary to conduct preliminary assessments of potential use across the spectrum of applications. Identifying applications will provide guidance on targeted material properties and inform design of future experiments.

PROJECT STATUS/RESULTS: Experiments at controlled reactor pressures are underway to better understand pressure's role in TPP biocarbon formation. These parametric tests will provide preliminary data needed to design a factorial experimental campaign to identify control variable interactions. Variables available to control reaction conditions include temperature, pressure, particle size, moisture content, bulk density, reactant gases, and reaction time, etc.

Figure 1. Transient plastic phase biocarbons.

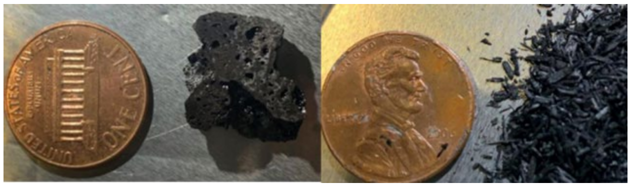


Figure 2. Transient plastic phase biocarbon on left and non-transient plastic phase biocarbon on the right. Both products made from the same biomass feedstock.

Funding Source: SINTEF Energy Research; Office of Naval Research

Contact: Scott Turn, sturn@hawaii.edu

Last Updated: November 2021

C5: Solar Fuels Generation

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 to 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 $CuInGaSe_2$, 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 $CuInGaSe_2$-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: 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 multiple fully integrated chalcopyrite devices onto each other to create multi-junction devices (Gaillard, 2019 presentation). We demonstrated that over 90% of the devices electrical properties are preserved after exfoliation and bonding, leading to multijunction structures capable of producing the large voltages required for water splitting.

This project has produced the following publications:

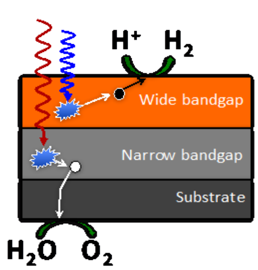
- 2019, T.R. Hellstern, et al., **Molybdenum Disulfide Catalytic Coatings via Atomic Layer Deposition for Solar Hydrogen Production from Copper Gallium Diselenide Photocathodes**, ACS Appl. Ener. Mats.
- 2019, N. Gaillard, et al., **Wide-Bandgap $Cu(In,Ga)S_2$ Photocathodes Integrated on Transparent Conductive $F{:}SnO_2$ Substrates for Chalcopyrite-Based Water Splitting Tandem Devices**, ACS Appl. Ener. Mats.
- 2019, N. Gaillard, **Novel Chalcopyrites for Advanced Photoelectrochemical Water-Splitting**, Presented at the U.S. DOE AMR.
- 2013, N. Gaillard, et al., **Development of Chalcogenide Thin Film Materials for Photoelectrochemical Hydrogen Production**, Proceeding of MRS Meeting.

Funding Source: U.S. Department of Energy

Contact: Nicolas Gaillard, ngaillar@hawaii.edu

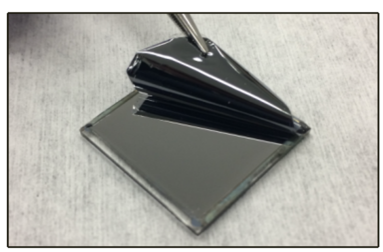
Last Updated: November 2021

Tandem PEC device concept



Bandgap tunable photoelectrodes

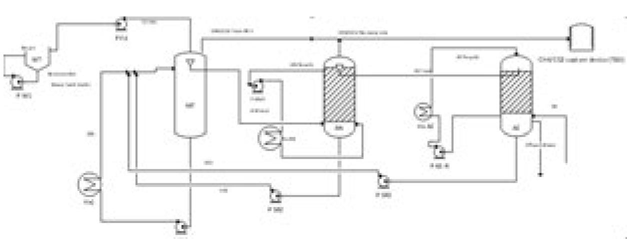
Transferable PEC layers for efficient devices



C6: High Rate Anaerobic-Aerobic Digestion

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.

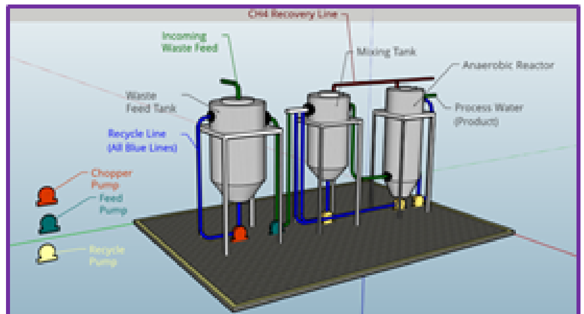


	Table 1	High Carbon Feed	Low Carbon Feed
Subsystems	Tanks/Reactor Vessels	$126,000.00	$126,000.00
	Pumps	$67,742.50	$71,000.00
	Sensors and Heaters	$30,661.20	$30,661.20
	Total	$224,403.70	$227,661.20

PROJECT STATUS/RESULTS: This project has produced a number of works that can be found on the following page. While this project was dormant during 2021, the PI continues to seek industrial partners to apply the system. The PI will support testing.

Funding Source: Office of Naval Research

Contact: Michael Cooney, mcooney@hawaii.edu

Last Updated: November 2021

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.

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, including developing components that enhance contaminant tolerance.

BACKGROUND: Electric propulsion offers several advantages over small hydrocarbon powered engines (e.g. 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. 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. Subsequently, NRL has continued to develop their own proprietary fuel cells and systems for UAV applications. HNEI has supported this effort, and continues to support this effort, via diagnostic testing, evaluation of needs, and design recommendations.

More recently, HNEI has shifted focus from testing support and is currently working on the design, development, and demonstration of PEM fuel cell components that enhance contaminant tolerance at elevated operating temperatures. Most industry wide efforts in contamination to date have primarily focused on low temperature (60-90°C) PEM fuel cells for transportation and unmanned vehicle applications. High temperature (140-200°C) PEM (¬HTPEM) fuel cells have the benefits of higher contaminant tolerance and lower cost membranes vs low temperature PEM (LTPEM) fuel cells. Additionally, the higher operating temperatures can help reduce the system complexity and provide opportunities for volume reduction (e.g. heat exchanger size reduction), a major consideration for use of fuel cells for small UAVs (1-10 kW).

Under this work, HNEI is establishing a fabrication system (Figure 1) based on the NRL design to enable in-house fabrication of custom catalyst coated membranes. The objective is to adapt the NRL protocol to work with high temperature materials with inherent contamination resistance. The ability to create custom catalyst coated membranes (CCMs) is an essential capability in the research and development of advanced electrocatalysts, gas diffusion media (GDM), ionomers, polymer electrolyte membranes (PEMs), and electrode structures designed for use in next-generation contaminant resistant fuel cells for UAVs.

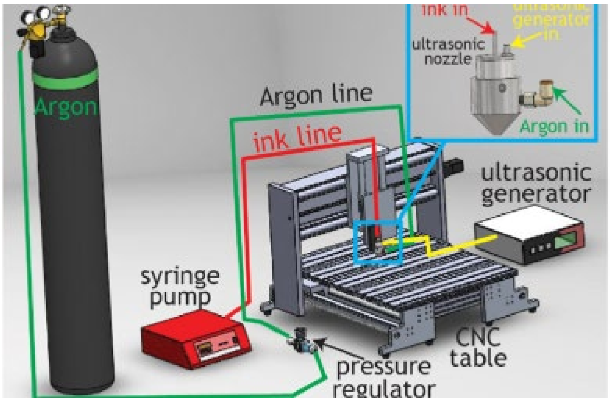


Figure 1. Ultrasonic spray coating system for in-house manufacturing of custom CCMs (insert).

PROJECT STATUS/RESULTS: HNEI has acquired equipment to establish capabilities to manufacture membrane electrode assemblies in-house to support the development of HTPEM components. Anticipated completion of the equipment installation and laboratory modifications is expected in early 2022. For additional information, refer to the publication listing on the following page.

Funding Source: Office of Naval Research

Contact: Keith Bethune, bethune@hawaii.edu

Last Updated: November 2021

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, K. Bethune, J. St-Pierre, J.M. LaManna, D.S. Hussey, and D.L. Jacobson, **Contamination Mechanisms of Proton Exchange Membrane Fuel Cells-Mass Transfer Overpotential Origin**, The Journal of Physical Chemistry C, Vol.124, Issue 44, pp. 24052-24065.
2. 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**)
3. 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, Hawaiʻi, 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.

D2: Proton Exchange Membrane Fuel Cell Contamination

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to develop an effective technique to mitigate or restore the performance loss caused by air contaminants in proton exchange membrane fuel cell (PEMFC) systems, especially the losses that cannot be restored by clean air operation. If successful, the technique would facilitate PEMFC systems meeting the U.S. DOE technical targets at performance and durability by inhibiting the degradations of membrane electrodes assembly (MEA) components and their performance. This program would help overcome the challenge of operating PEMFC systems in polluted or other harsh environments.

BACKGROUND: PEMFCs are considered a promising clean energy technology for transportation and stationary applications. Currently, Pt-based catalysts are used almost exclusvely in PEMFC due to the high electrochemical activity. Unfortunately, air pollution is a challenge for the PEMFC applications in the realistic atmosphere. There are more than 200 airborne pollutants, which may be introduced into the PEMFC cathode via the air stream with the potential to poison the Pt-based catalysts.

In past decades, PEMFC 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 tests. Most of these compounds are able to adsorb and react on Pt surface and compete with oxygen reduction reaction, a key reaction in PEMFC. While the effects from both unsaturated hydrocarbon and oxygen-containing hydrocarbon contaminants, could be mitigated by interrupting the explosure to contaminants for sulfur and halogen compounds degrade cell performance that does not recover with clean air operation. The contamination also accelerates the permanent degradation of Pt catalysts and electrolyte membrane. The contamination mechanisms of those compounds (e.g. bromomethane) are illustrated in Figure 1. The contaminants permeate through the thin ionomer film and break down to adsorbates ($BrCH_3$ to Br^-, SO_2 to S and 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-electrolyte film 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.

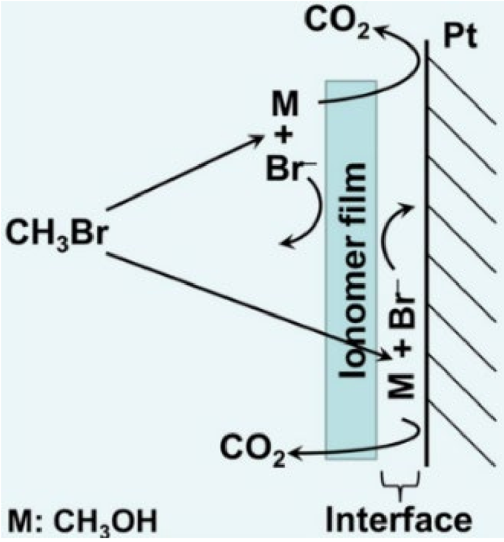


Figure 1. Contamination mechanisms of bromomethane in PEMFC cathode.

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, HNEI has developed performance recovery techniques that, in once case incorporates a combination of purging and flushing operations; and in other cases, uses an in-situ catalytically filtration method to eliminate the contaminants before it reaches the catalysts layer. The specific procedures are based on a comprehensive understanding on the contamination mechanisms of the selected air pollutants. The recovery 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.

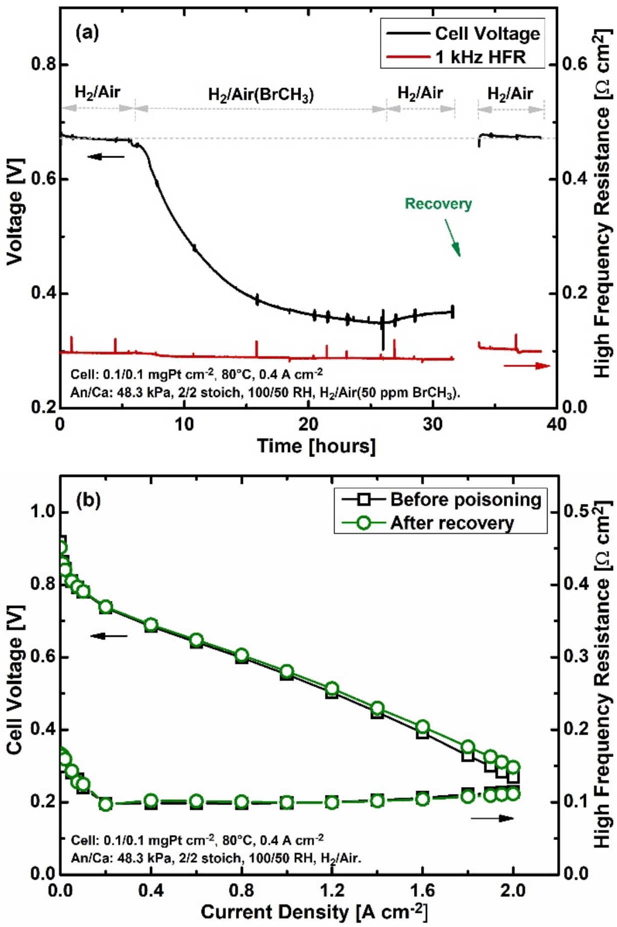


Figure 2. (a) Cell performance responses to the bromomethane contamination and recovery; (b) Cell polarization curves before poisoning and after recovery.

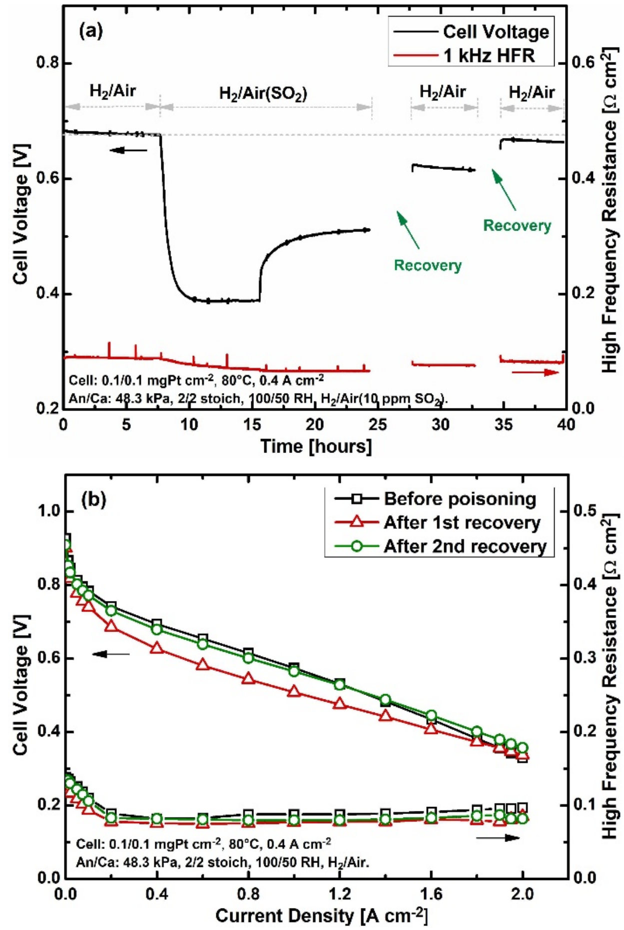


Figure 3. (a) Cell performance responses to the sulfur dioxide contamination and recovery; (b) Cell polarization curves before poisoning and after recovery.

In summary, an effective recovery method has been developed and demonstrated that yields almost complete performance recovery after poisoning with bromomethane, hydrogen chloride, or sulfur dioxide. A provisional patent was filed. Collaboration with the PEMFC stacks manufactures, who are running fuel cell vehicle demonstrations, is being sought for further validating the efficiency of the recovery method for contaminated PEMFC stacks. And several novel catalysts for the selected air pollutants are being developed for the in-situ catalytically filtration method.

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

Contact: Yunfeng Zhai, yunfeng@hawaii.edu.

Last Updated: November 2021

D3: Anion Exchange Membrane Fuel Cell

Objective and Significance: The goals of this project are to 1) evaluate the performance of anion exchange membrane fuel cells (AEMFCs) with platinum group metal (PGM) content and PGM-free cathode catalysts under various operating conditions and 2) advance the understanding of effects of membrane electrode assemblies (MEAs) components on mass transport, water management, and durability.

Background: Interest in AEMFCs technology (Figure 1) has been driven by the possible use of PGM-free catalysts instead of Pt at the anode and cathode enabled by the use of an alkaline electrolyte.

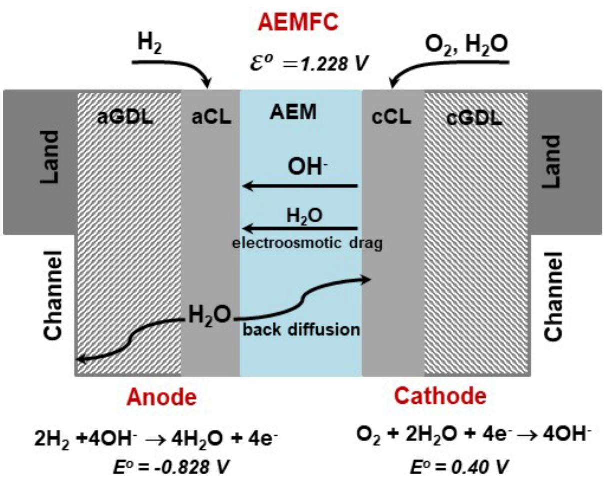


Figure 1. Schematic representation of AEMFC.

A logical step would 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 approach to improve AEMFC performance and durability is a design of catalyst layers with optimal porosity, hydroxide ion conductivity and thickness to insure development of three phase boundaries and sufficient reagents transport as well as adequate choice of gas diffusion layers (GDLs) for better water management.

Project Status/Results: Under this effort, HNEI has

- Demonstrated that 25 wt.% ionomer loading is sufficient to ensure high performance of AEMFC;
- Established set of electrochemical diagnostics for AEMFCs including polarization curves, cyclic voltammetry and application of electrochemical impedance spectroscopy;
- Studied effects of inlet gas humidification and cathode feed gas configuration (O_2 vs air) on the performance of AEMFCs (Figure 2); and
- Continued to establish fuel cell testing capabilities at the UH Mānoa campus following the 2020 closure of HiSERF.

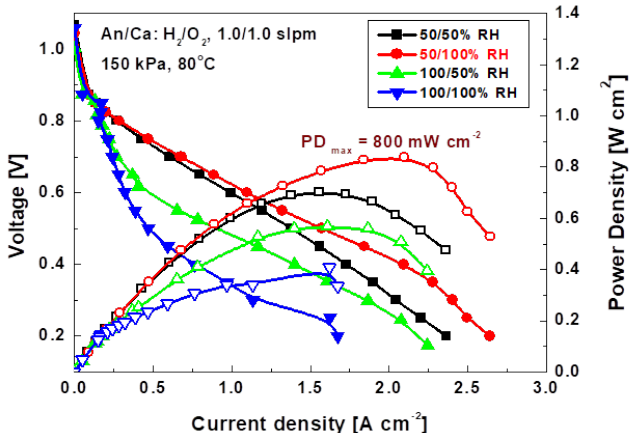


Figure 2. Polarization curves for different AEMFCs operated at various inlet gas humidification.

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

Last Updated: November 2021

D4: PGM-Free Catalysts for PEM Fuel Cell Applications

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, HNEI is 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 (NO_2, SO_2), which typically seriously affect Pt-based PEMFC performance.

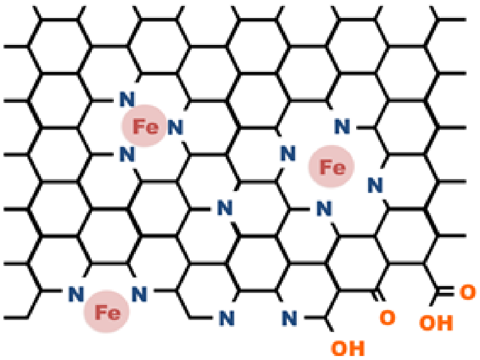


Figure 1. Schematic representation of PGM-free catalyst with Fe-Nx active sites. (2014, A. Serov, et al., Advanced Energy Materials, 4, 1301735).

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 (Figure 1). 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. PGM-free fuel cell performance can be improved by designing and optimizing the cathodic catalyst layer (CL) and MEA construction such that: 1) it efficiently provides oxygen access to Fe-Nx active sites (through catalyst morphology control), 2) it removes water from the CL (by tuning the hydrophobicity of the PGM-free catalysts and the catalyst layer structure), and 3) it increases proton conductivity (by homogeneous mixing of catalysts and ionomer). Studying the CL is complex due to the absence of well-established protocols of MEA activation and testing especially compared to Pt-containing catalysts. PGM-free fuel cell testing protocols need to optimize potentiostatic vs. galvanostatic measurements, scan rates, parameters of electrochemical impedance spectroscopy (EIS) and evaluation criteria.

Thus, 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 joint collaboration between industry (Pajarito Powder LLC, IRD Fuel Cell) and academia (HNEI) and is funded under U.S. Department of Energy project "Active and durable PGM-free cathodic electrocatalysts for fuel cell application" (DE-EE0008419). HNEI's role is to conduct electrochemical evaluation of the PGM-free PEMFCs using advanced and proven electrochemical techniques.

Project Status/Results: Initiated in 2019, the project has produced several accomplishments.

Four generations of PGM-free electrocatalysts were synthesized using sacrificial support method and rationally selected precursors, conditions and treatments (Figure 2, on the following page). An application of high surface silica resulted in formation of several levels of catalysts porosity and led to 2nd catalyst generation.

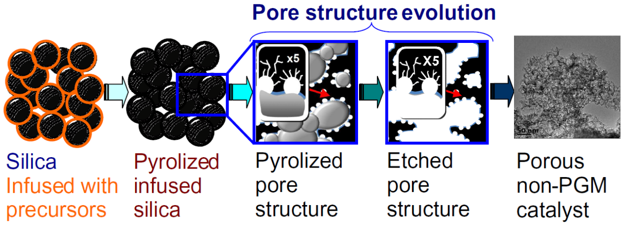


Figure 2. General schematic of used sacrificial support method for Fe-N-C catalyst synthesis.

3rd generation of the PGM-free catalysts was obtained by further catalyst treatment by NH_3 at elevated temperature. The chosen methodology led to formation of atomically dispersed Fe-N_x moieties and increase its amount due to creation of additional defects in carbon matrix (Figure 3). Raman spectroscopy demonstrated that materials maintains substantial level of graphitization.

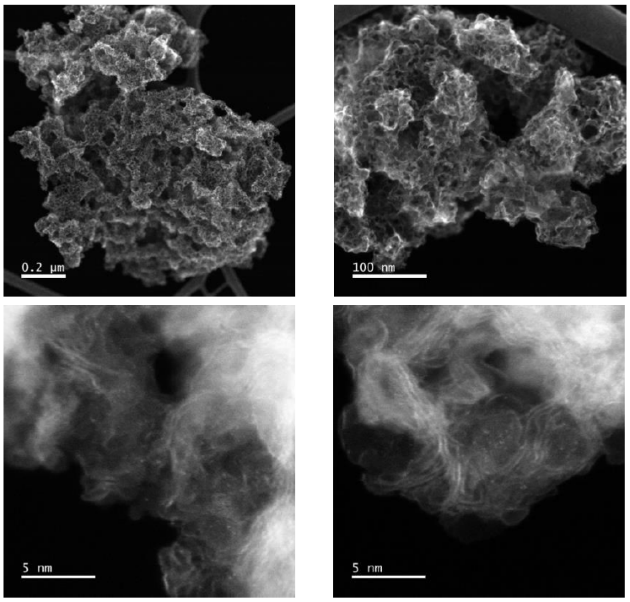


Figure 3. SEM and HRTEM images of 3rd generation of Fe-N-C catalysts (NH_3 treated).

PGM-free electrocatalysts are typically characterized by large primary catalyst particles with size higher than 1 μm, which affects where integration into the electrode structure and negatively impacted development of 3 phase boundaries and proton conductivity. In order to reduce their size additional pore-forming agents were introduced during catalyst synthesis and resulted to 4th generation of the PGM-free catalysts (Figure 4). The size of the primary catalyst particles decreased to 300-400 nm, while the catalysts surface area increased to 820 m^2 g^{-1}.

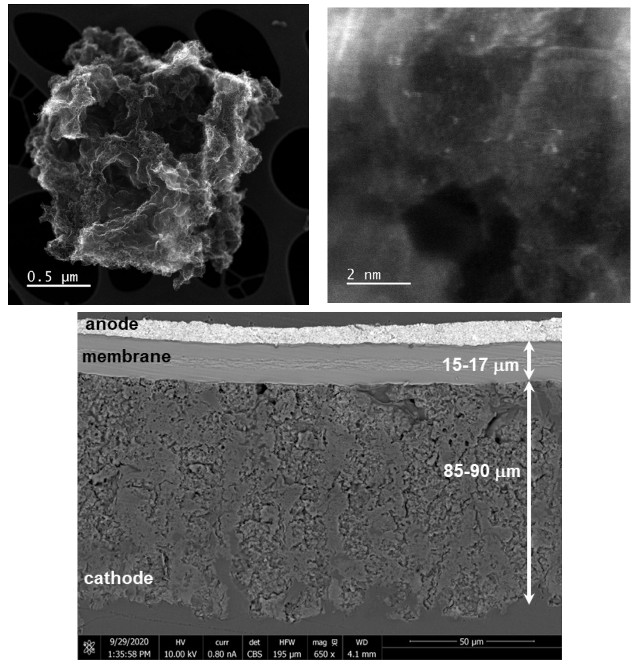


Figure 4. SEM and HRTEM images of 4th generation of Fe-N-C catalysts and MEA cross section. Atomically dispersed Fe-N_x centers are presented as bright dots at TEM images.

The electrocatalysts were successfully integrated into electrode structures. For understating effects of MEAs components on fuel cell performance, we evaluated the following parameters: membrane thickness (15-175 μm); ionomer type, ionomer equivalent weight (EW) and its loading in the cathode electrode (30-60%); PGM-free catalyst content (0.5-6.0 mg cm^{-2}) and electrode structure design.

A testing protocol for PGM-free PEMFCs evaluation was established and included measurements of polarization curves from ocv to 0.6 V and from ocv to 0.2 V in forward and backward directions with simultaneous detection of HFR at 1kHz; electrochemical impedance spectroscopy (EIS) and cyclic voltammetry to obtain double layer capacitance and access MEAs integrity (lack of electrical short).

There were evaluated ~100 MEAs. The best results were obtained for membrane LYT 0009 with thickness of 18 μm, with PGM-free loading of 2-3 mg cm-2, 40-45% ionomer loading with EW720. Figure 5 on the following page shows improvement in performance of the different generations of PGM-free electrocatalysts in comparison with Pt based fuel cell.

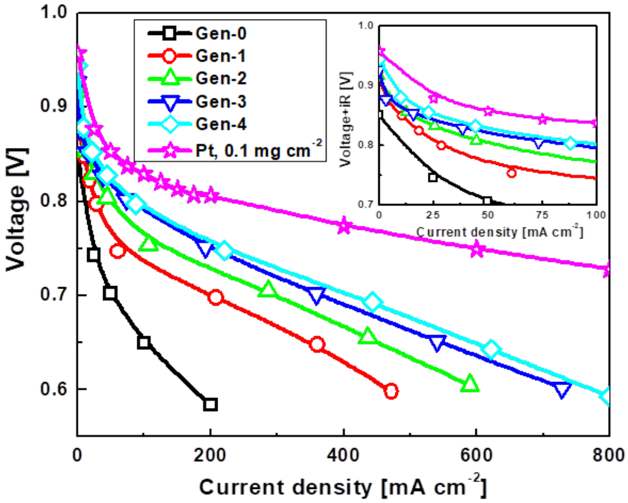


Figure 5. Polarization curves for different generation of PGM-free and Pt-based MEAs. An/Ca: H_2/O_2, 0.5 slpm, 100%RH, 150 kPa, T_{cell}=80°C.

Physic-based EIS models were adapted for fitting PGM-free impedance data and used to assess main kinetic (Tafel slope) and mass transport parameters (proton conductivity, O_2 diffusivity). New generation of the MEAs demonstrated that proton conductivity of the PGM-free cathode was improved significantly from 5-10 to 30-40 mS cm^{-1} as well as O_2 diffusivity in the cathode structure. Moreover, the developed family of PGM-free electrocatalysts were determined to be highly selective towards 4 e^- oxygen reduction mechanism, which explains performance and efficiency of the catalysts. The team successfully passed intermediate milestone of 44 mA cm^{-2} at 0.85 V and reached Go-no-Go target of 22-27 mA cm^{-2} at 0.9 V.

This project produced a number of works, including the ones listed below:

- 2020, T. Reshetenko, et al., **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**)
- 2020, T. Reshetenko, et al., **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**)
- 2020, T. Reshetenko, et al., **Effects of cathode proton conductivity on PGM-free PEM fuel cell performance**, Presented at the ECS 2020-02 Meeting, Honolulu, Hawaiʻi, October 4-9, Abstract 2686.
- 2019, T. Reshetenko, et al., **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**)
- 2019, T. Reshetenko, et al., **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.
- 2019, A. Serov, et al., **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.

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

Contact: Tatyana Reshetenko, tatyanar@hawaii.edu

Last Updated: November 2021

D5: Transition Metal Carbide Catalysts for Electrochemical Applications

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 (VRFBs).

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. VRFBs have recently attracted considerable attention for large-scale energy storage. Carbon-based 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. 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. 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. Figure 1 indicates that C and V elements are distributed uniformly for vanadium carbide on Vulcan XC72 (VC_{XC72}). VC_{XC72} contains 29 atom% vanadium and 71 atom% carbon, corresponding to 76.5 wt.% V_8C_7 on Vulcan XC72. Figure 2 shows the catalytic activity of graphite and VC_{XC72} after background current subtraction. The peak potential separation ($\Delta E_p = E_{pa} - E_{pc}$) and peak current ratio (I_{pa}/I_{pc}) indicate the reversibility of a redox couple. The vanadium carbide-modified electrode exhibits lower ΔE_p value than the pristine graphite electrode. The I_{pa}/I_{pc} for VC_{XC72} is closer to 1 than that for graphite, which also indicates enhanced reversibility toward V^{3+}/V^{2+} redox reactions. Future studies will include modifications to the catalyst synthesis approach to increase the activity by tuning the catalyst structure and morphology.

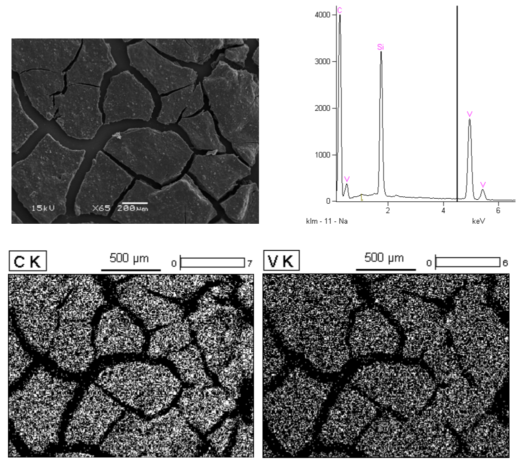


Figure 1. Scanning electron microscopy and energy dispersive X-ray spectroscopy analysis of vanadium carbide on Vulcan XC72 (VC_{XC72}).

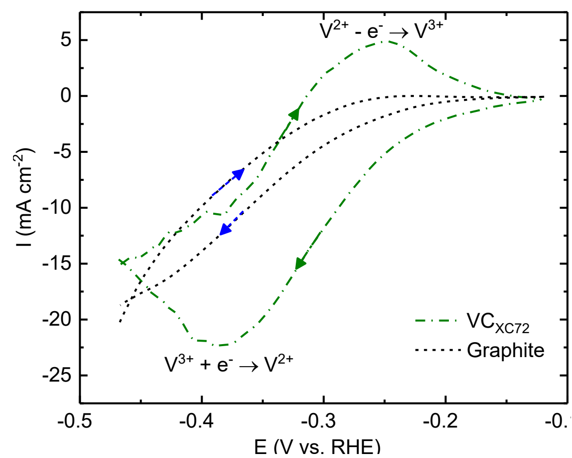


Figure 2. Cyclic voltammograms on various electrodes at 5mV s^{-1} in N_2 saturated 3 M H_2SO_4 + 1 M V^{3+}/V^{2+} at 25°C.

Funding Source: Office of Naval Research

Contact: Jing Qi, qijing@hawaii.edu

Last Updated: November 2021

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 and how to monitor them better. 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. Throughout the course of this project, three BESS serving different grid applications were deployed on different islands. 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. 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 Lithium titanate cells 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 their lower intrinsic 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.

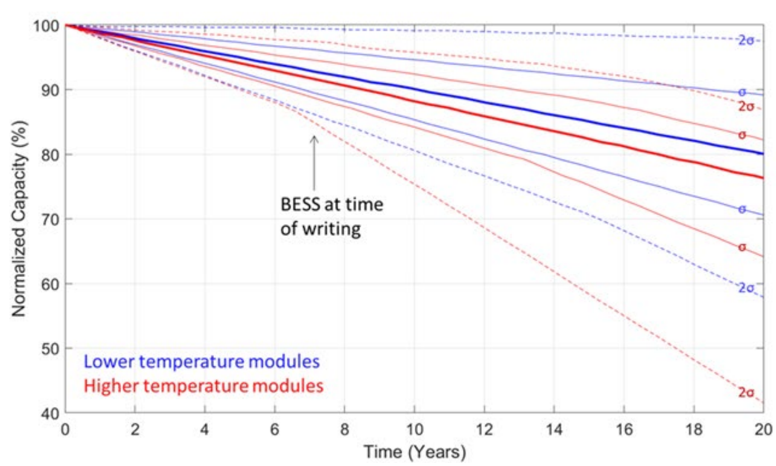
Based on our results, we are projecting that accelerated degradation, a typical occurrence in traditional lithium ion batteries, remains of concern under certain conditions, notably if the cells are kept consistently above 35ºC, which does not appear to the case on the deployed data. Therefore, a 20-year grid usage should be attainable for these Lithium Titanate cells with a total capacity loss around 20%. Results also showed that the capacity monitoring of deployed systems might not be accurate and that new tracking methods are necessary. Research conducted for this project is completed in the **PakaLi Battery Laboratory**.

This is an ongoing project, which has led to 11 publications, including the ones listed on the following page.

Funding Source: Office of Naval Research

Contact: Matthieu Dubarry, matthieu@hawaii.edu; Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2021



Additional Project Related Links

Papers and Proceedings:

1. 2021, M. Dubarry, et al., **Battery Durability and Reliability under Electric Utility Grid Operations: Analysis of On-Site Reference Tests**, Electronics, Vol. 10, Issue 13, Paper 1593. (Open Access: **PDF**)
2. 2019, G. Baure, et al., **Battery Durability and Reliability under Electric Utility Grid Operations: Path Dependence of Battery Degradation**, Journal of the Electrochemical Society, Vol. 166, Issue 10, pp. A1991-A2001. (Open Access: **PDF**)
3. 2019, M. Dubarry, et al., **Battery energy storage system modeling: Investigation of intrinsic cell-to-cell variations**, Journal of Energy Storage, Vol. 23, pp. 19-28. (Open Access: **PDF**)
4. 2019, M. Dubarry, et al., **Battery energy storage system modeling: A combined comprehensive approach**, Journal of Energy Storage, Vol. 21, pp. 172-185. (Open Access: **PDF**)
5. 2018, K. Stein, et al., **Evaluation of a 1 MW, 250 kW-hr Battery Energy Storage System for Grid Services for the Island of Hawai‘i**, Energies, Vol. 11, Issue 12, Paper 3367. (Open Access: **PDF**)
6. 2018, K. Stein, et al., **Characterization of a Fast Battery Energy Storage System for Primary Frequency Response**, Energies, Vol. 11, Issue 12, Paper 3358. (Open Access: **PDF**)
7. 2018, M. Dubarry, et al., **Battery durability and reliability under electric utility grid operations: Representative usage aging and calendar aging**, Journal of Energy Storage, Vol. 18, pp. 185-195.
8. 2017, M. Dubarry, et al., **Battery Energy Storage System battery durability and reliability under electric utility grid operations: Analysis of 3 years of real usage**, Journal of Power Sources, Vol. 338, pp. 65-73.
9. 2016, A. Devie, et al., **Overcharge Study in $Li_4Ti_5O_{12}$ Based Lithium-Ion Pouch Cell, II. Experimental Investigation of the Degradation Mechanism**, Journal of Electrochemical Society, Vol. 163, Issue 13, pp. A2611-A2617. (Open Access: **PDF**)
10. 2015, A. Devie, et al., **Overcharge study in $Li_4Ti_5O_{12}$-based Lithium-ion pouch cell. Part I: Quantitative diagnosis of degradation modes**, Journal of The Electrochemical Society, Vol. 162, Issue 6, pp. A1033-A1040. (Open Access: **PDF**)

Presentations:

1. 2021, M. Dubarry, G. Baure, **Battery Durability and Reliability under Electric Utility Grid Operations**, Presented at the International Battery Seminar & Exhibit, March 9-11.
2. 2021, M. Dubarry, **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the Alaska Energy Storage Workshop, January 12-13.
3. 2020, G. Baure, D. Beck, M. Dubarry, **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the ECS PRiME Meeting, October 4-9.
4. 2020, M. Dubarry, G. Baure, **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the International Coalition for Energy Storage and Innovation Conference, Sydney, Australia, March 1-4.
5. 2019, M. Dubarry, A. Devie, G. Baure, **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the International Battery Association Meeting, March 3-8.
6. 2018, A. Devie, G. Baure, M. Dubarry, **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the ECS AiMES Meeting, Cancun, Mexico September 30 - October 4.
7. 2017, M. Dubarry, R. Rocheleau, **Asia Pacific Research Initiative for Sustainable Energy Systems: Batteries for Grid Management**, Presented at the ONR Program Review, Washington, DC, March 28-30.
8. 2016, M. Dubarry, **Overcharge Study in Li4Ti5O12 Based Lithium-Ion Pouch Cell**, Presented at the International Battery Association Meeting, Nantes, France, March 20-25.

D7: Path Dependence of Battery Degradation

<u>Objective and Significance</u>: The objective of this project is to characterize the impact of different stresses on the durability of Li-ion batteries using large experimental campaigns and design of experiments. Studies could address, among others, the impact of fast charging and grid-vehicle interactions on the performance of batteries for electric transportation. The knowledge gained in this project inform best practices to successful battery durability, safety, fast charging, or vehicle-to-X integration.

<u>Background</u>: Electrification of transportation and grid-storage are crucial to combat climate change. Understanding and mitigating battery degradation is key to improving durability of electric transportation and the reliability of power grids. Complexity stems from the fact that battery degradation is path dependent. This implies that usage affects not only the degradation pace, 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 mix of degradation mechanisms and thus on how the battery was used. To maximize the utility of large battery systems, it is essential to understand the impact of all the stress factors associated with an application and their combined effects.

<u>Project Status/Results</u>: Our study already 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. We also 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. It must be noted that, because of path dependence, different usages might lead to different results and thus that our results should not yet be generalized on cells different than the one tested.

Current work with DSTG (Australia) involves an experimental campaign of more than 700 cells tested under a HNEI defined design of experiments to predict the degradation of MW systems and maximize their durability and reliability in the field.

Research conducted for this project is completed in the **PakaLi Battery Laboratory**. This project is ongoing and already led to 10 publications, which are listed on the following page.

Funding Source: Office of Naval Research; Defence Science and Technology Group (Australia)

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2021

ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

1. 2021, D. Beck, et al., **Inhomogeneities and Cell-to-Cell Variations in Lithium-Ion Batteries, a Review**, Energies, Vol. 14, Issue 11, Paper 3276. (Open Access: **PDF**)
2. 2020, M. Elliott, et al., **Degradation of electric vehicle lithium-ion batteries in electricity grid services**, Journal of Energy Storage, Vol. 32, Paper 101873.
3. 2020, G. Baure, et al., **Durability and Reliability of EV Batteries under Electric Utility Grid Operations: Impact of Frequency Regulation Usage on Cell Degradation**, Energies, Vol. 13, Issue 10, Paper 2494. (Open Access: **PDF**)
4. 2019, G. Baure, et al., **Synthetic vs. Real Driving Cycles: A Comparison of Electric Vehicle Battery Degradation**, Batteries, Vol. 5, Issue 2, Paper 42. (Open Access: **PDF**)
5. 2018, M. Dubarry, et al., **Durability and Reliability of EV Batteries under Electric Utility Grid Operations: Path Dependence of Battery Degradation**, Journal of the Electrochemical Society, Vol. 165, Issue 5, pp. A773-A783. (Open Access: **PDF**)
6. 2018, K. Uddin, et al., **The viability of vehicle-to-grid operations from a battery technology and policy perspective**, Energy Policy, Vol. 113, pp. 342-347. (Open Access: **PDF**)
7. 2017, M. Dubarry, et al., **Durability and Reliability of Electric Vehicle Batteries Under Electric Utility Grid Operations: Bidirectional Charging Impact Analysis**, Journal of Power Sources, Vol. 358, pp. 39-49.
8. 2017, D. Ansean, et al., **Operando lithium plating quantification and early detection of a commercial $LiFePO_4$ cell cycled under dynamic driving schedule**, Journal of Power Sources, Vol. 356, pp. 36-46.
9. 2016, A. Devie, et al., **Durability and reliability of electric vehicle batteries under electric utility grid operations. Part 1: Cell-to-cell variations and preliminary testing**, Batteries, Vol. 2, Issue 3, paper 28. (Open Access: **PDF**)
10. 2016, D. Ansean, et al., **Fast charging technique for high power LiFePO4 batteries: a mechanistic analysis of aging**, Journal of Power Sources, Vol. 321, pp. 201-209.

PRESENTATIONS:

1. 2019, M. Dubarry, G. Baure, **Synthetic vs. Real Driving Cycles: A Comparison of EV Battery Degradation**, Presented at the 236th ECS Meeting, Atlanta, Georgia, October 13-17.
2. 2019, G. Baure, M. Dubarry, **A Diagnostic and Prognostic Study of the Impact of Electric Utility Grid Operations on EV Batteries**, Presented at the International Coalition for Energy Storage and Innovation Meeting, Waikoloa, Hawaiʻi, January 5-10.
3. 2017, A. Devie, G. Baure, M. Dubarry, **Durability and Reliability of EV Batteries under Electric Utility Grid Operations**, Presented at the 232nd ECS Meeting, National Harbor, Maryland, October 1-5.
4. 2016, M. Dubarry, A. Devie, **Path Dependence in Lithium-Ion Batteries Degradation**, Presented at the ECS PRiME Meeting, Honolulu, Hawaiʻi, October 2-7.
5. 2016, M. Dubarry, A. Devie, **EV Cell Degradation under Electric Utility Grid Operations**, Presented at the Next-Generation Energy Storage Conference, San Diego, California, April 18-19.
6. 2015, A. Devie, M. Dubarry, B.Y. Liaw, **Investigation of Consistency of Aging Mechanism inside a Batch of Commercial 18650 Lithium-ion Cells**, Presented at the 225th ECS Meeting, Orlando, Florida, May 11-15.
7. 2015, M. Dubarry, A. Devie, B.Y. Liaw, **Experimental diagnostic of Li-ion commercial cells, case studies**, Presented at the 225th ECS Meeting, Orlando, Florida, May 11-15.

D8: Battery Intelligence: Diagnosis and Prognosis

OBJECTIVE AND SIGNIFICANCE: This project aims at the development of approaches, tools, and protocols, 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 type of degradation. In addition, since large battery packs are composed of thousands of cells, the use of complex models or a multitude of sensors for each cell is precluded.

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 – uses as little resources as possible and must not be destructive. As a result, it is ineffective in predicting the true state of health.

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 cost-effective and non-destructive methods, using only sensors already available in battery packs while requiring limiting computing power.

HNEI developed a mechanistic modeling framework where a battery digital twin is built from individual electrode data and where the battery degradation is emulated by the scaling or the translation of one electrode versus the other. Using this framework, the voltage variations associated with the degradation mechanisms can be predicted.

Machine learning and artificial intelligence are also 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 applied the mechanistic modeling approach to develop the first synthetic training datasets using computer-generated voltage curves. Research conducted for this project is completed in the PakaLi Battery Laboratory.

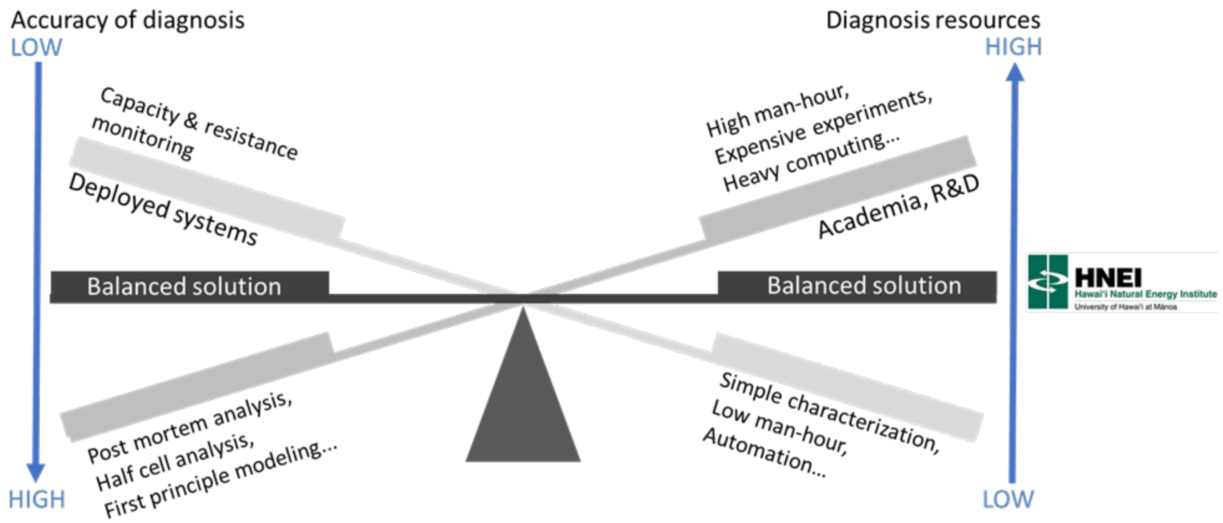
PROJECT STATUS/RESULTS: This project is currently ongoing with three industrial collaborations on different aspects of the problem. A full suite of software and models were developed. The main model has been licensed by more than 65 organizations worldwide.

This work led to 36 publications, including the ones listed on the following page and one patent.

Funding Source: Office of Naval Research; SAFT (France); Element Energy; ACCURE (Germany)

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2021



Additional Project Related Links

Papers and Proceedings:

Battery Testing

1. 2021, M. Dubarry, D. Beck, **Analysis of Synthetic Voltage vs. Capacity Datasets for Big Data Li-ion Diagnosis and Prognosis**, Energies, Vol. 14, Issue 9, Paper 2371. (Open Access: **PDF**)
2. 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.
3. 2020, D. Anseán, G. Baure, M. González, I. Cameán, A.B. García, M. Dubarry, **Mechanistic investigation of silicon-graphite/$LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ commercial cells for non-intrusive diagnosis and prognosis**, Journal of Power Sources, Vol. 459, Paper 227882.
4. 2020, M. Dubarry, G. Baure, **Perspective on Commercial Li-ion Battery Testing, Best Practices for Simple and Effective Protocols**, Electronics, Vol. 9, Issue 1, Paper 152. (Open Access: **PDF**)
5. 2019, A. Barai, K. Uddin, M. Dubarry, L. Somerville, A. McGordon, P. Jennings, I. Bloom, **A comparison of methodologies for the non-invasive characterisation of commercial Li-ion cells**, Progress in Energy and Combustion Science, Vol. 72, pp. 1-32. (Open Access: **PDF**)
6. 2018, M. Dubarry, Q. Nan, P. Brooker, **Calendar aging of commercial Li-ion cells of different chemistries – A review**, Current Opinion in Electrochemistry, Vol. 9, pp. 106-113.
7. 2018, A. Devie, G. Baure, M. Dubarry, **Intrinsic Variability in the Degradation of a Batch of Commercial 18650 Lithium-Ion Cells**, Energies, Vol. 11, Issue 5, Paper 1031. (Open Access: **PDF**)
8. 2018, C.T. Love, M. Dubarry, T. Reshetenko, A. Devie, N. Spinner, K.E. Swider-Lyons, R. Rocheleau, **Lithium-Ion Cell Fault Detection by Single-Point Impedance Diagnostic and Degradation Mechanism Validation for Series-Wired Batteries Cycled at 0 °C**, Energies, Vol. 11, Issue 4, Paper 834. (Open Access: **PDF**)
9. 2017, D. Ansean, M. Dubarry, A. Devie, B.Y. Liaw, V.M. Garcia, J.C. Viera, M. Gonzalez, **Operando lithium plating quantification and early detection of a commercial $LiFePO_4$ cell cycled under dynamic driving schedule**, Journal of Power Sources, Vol. 356, pp. 36-46.
10. 2016, D. Ansean, M. Dubarry, A. Devie, B.Y. Liaw, V.M. Garcia, J.C. Viera, M. Gonzalez, **Fast charging technique for high power $LiFePO_4$ batteries: a mechanistic analysis of aging**, Journal of Power Sources, Vol. 321, pp. 201-209.

Battery Modeling

1. 2019, S. Schindler, G. Baure, M.A. Danzer, M. Dubarry, **Kinetics accommodation in Li-ion mechanistic modeling**, Journal of Power Sources, Vol. 440, Paper 227117.
2. 2019, M. Dubarry, C. Pastor-Fernández, G. Baure, T.F. Yu, W.D. Widanage, J. Marco, **Battery energy storage system modeling: Investigation of intrinsic cell-to-cell variations**, Journal of Energy Storage, Vol. 23, pp. 19-28. (Open Access: **PDF**)
3. 2019, M. Dubarry, G. Baure, C. Pastor-Fernández, T.F. Yu, W.D. Widanage, J. Marco, **Battery energy storage system modeling: A combined comprehensive approach**, Journal of Energy Storage, Vol. 21, pp. 172-185. (Open Access: **PDF**)
4. 2017, M. Dubarry, M. Berecibar, A. Devie, D. Ansean, N. Omar, I. Villarreal, **State of Health Battery Estimator Enabling Degradation Diagnosis: Model and Algorithm Description**, Journal of Power Sources, Vol. 360, pp. 59-69.
5. 2016, M. Dubarry, A. Devie, B.Y. Liaw, **Cell-balancing currents in parallel strings of a battery system**, Journal of Power Sources, Vol. 321, pp. 36-46.
6. 2016, M. Berecibar, M. Dubarry, N. Omar, I. Villarreal, J. Van Mierlo, **Degradation Mechanism Detection for NMC Batteries based on Incremental Capacity Curves**, World Electric Vehicle Journal, Vol. 8, Issue 2, pp. 350-361. (Open Access: **PDF**)

7. 2016, M. Berecibar, F. Devriendt, M. Dubarry, I. Villarreal, N. Omar, W. Verbeke, J. Van Mierloz, **Online State of Health estimation on NMC cells based on Predictive Analytics**, Journal of Power Sources, Vol. 320, pp. 239-250.
8. 2016, M. Berecibar, M. Dubarry, I. Villarreal, N. Omar, J. Van Mierlo, **Degradation Mechanisms Detection for HP and HE NMC Cells Based on Incremental Capacity Curves**, Proceeding of the IEEE Vehicle Power and Propulsion Conference (VPPC), INSPEC 16558169.
9. 2015, M. Berecibar, N. Omar, M. Garmendia, I. Villarreal, P. Van den Bossche, J. Van Mierlo, M. Dubarry, **SOH estimation and prediction for NMC cells based on degradation mechanism detection**, Proceeding of the IEEE Vehicle Power and Propulsion Conference (VPPC), INSPEC 15678053.
10. 2015, M. Dubarry, C. Truchot, A. Devie and B. Y. Liaw, **State-of-charge determination in lithium-ion battery packs based on two-point measurements in life**, Journal of The Electrochemical Society, Vol. 162, Issue 6, pp. A877-A884. (Open Access: **PDF**)

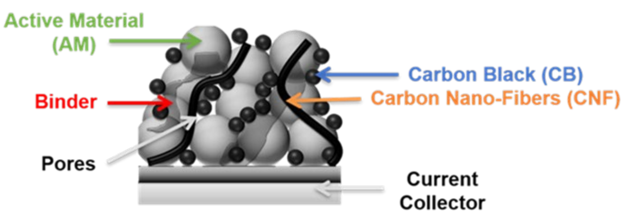
PRESENTATIONS:

1. 2021, M. Dubarry, D. Beck, **Big Data for Li-Ion Battery Diagnosis and Prognosis**, Presented at the Advanced Automotive Battery Conference, San Diego, California, December 7-9.
2. 2021, M. Dubarry, D. Beck, **A New Insight into Blended Electrodes**, Presented at the 240th ECS Meeting, Orlando, Florida, October 10-14.
3. 2021, M. Dubarry, D. Beck, **Big Data for Li-Ion Diagnosis and Prognosis**, Presented at the 239th ECS Meeting, May 30 - June 3.
4. 2020, M. Dubarry, D. Beck, **Synthetic Training Data for Artificial Intelligence-Based Li-Ion Diagnosis and Prognosis**, Presented at the ECS PRiME Meeting, October 4-9.
5. 2017, M. Dubarry, **Non-intrusive operando battery diagnosis and prognosis**, Presented at the Pacific Rim Conference on Ceramic and Glass Technology Meeting, Waikoloa, Hawaiʻi, May 21-26.
6. 2016, D. Anseán, M. Dubarry, A. Devie, B.Y. Liaw, V.M. García, J.C. Viera, M. González, **Lithium Plating Quantification in Commercial Graphite‖$LiFePO_4$ Batteries**, Presented at the ECS PRiME Meeting, Honolulu, Hawaiʻi, October 2-7.
7. 2015, A. Devie, M. Dubarry, P. Cabanel, B.Y. Liaw, **Intrinsic degradation variability in commercial lithium-ion batteries**, Presented at the 228th ECS Meeting, Phoenix, Arizona, October 11-16.
8. 2015, M. Dubarry, A. Devie, P. Cabanel, B.Y. Liaw, **State-of-Charge determination in imbalanced lithium-ion battery packs**, Presented at the 228th ECS Meeting, Phoenix, Arizona, October 11-16.
9. 2015, M. Dubarry, C. Truchot, A. Devie, B.Y. Liaw, **Two-point State of Charge Determination In Lithium-Ion Battery Packs**, Presented at the 227th ECS Meeting, Chicago, Illinois, May 24-28.
10. 2015, M. Dubarry, C. Truchot, A. Devie, B.Y. Liaw, **Two-point State of Charge Determination In Lithium-Ion Battery Packs**, Presented at the International Battery Association Meeting, Waikoloa, Hawaiʻi, January 5-9.

D9: Battery Electrode Optimization

OBJECTIVE AND SIGNIFICANCE: This project aims at the optimization of battery electrodes to improve performance by understanding local degradation mechanisms and by tuning the electrode 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 our expertise in Li-ion batterie diagnosis as well as designs of Experiments (DoE) 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 use 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.

In this project, the DoE approach is applied to two types of electrodes: high power electrodes for lithium batteries (ONR funded, in collaboration with the University of Montreal) and sodium intercalation electrodes (DOI funded, in collaboration with Trevi Systems) to investigate the feasibility of desalination batteries.

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 two publications. Current work is focused on the desalination with the optimization of Prussian blue analogues for Na ion intercalation in seawater. We are currently running experiments with materials able to intercalate and release sodium ions in real sea water more than 1000 times.

In addition, our expertise in battery degradation was used to help researchers at the Navy Research Laboratory to characterize the impact of local temperature gradients on individual electrodes and by researchers at SANDIA National Laboratory to investigate the impact of overcharge and depth of discharge.

Research conducted for this project is completed in the **PakaLi Battery Laboratory**. This program led to the three publications and a presentation (listed below) and a review so far.

- 2021, R. Carter, et al., **Directionality of thermal gradients in lithium-ion batteries dictates diverging degradation modes**, Cell Reports Physical Science, Vol. 2, Issue 2, Paper 100351. (Open Access: **PDF**)
- 2021, T.A. Kingston, et al., **Altering the Degradation Mode in Li-ion Batteries Through Directional Application of an Interelectrode Thermal Gradient**, Presented at the International Mechanical Engineering Congress & Exposition, November 1-5.
- 2020, O. Rynne, et al., **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, et al., **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

Collaborations: University of Montreal (Canada), University of Nantes (France), Navy Research Laboratory, SANDIA National Laboratory

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2021

D10: Vanadium Flow Battery with High Concentration Electrolytes

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 novel catalysts and 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. This work would facilitate the VFB system achieving the durability and cost required for large-scale energy storage applications.

BACKGROUND: A flow battery is an electrochemical device that comprises of 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 power density of VFBs depends on the redox reactions activities and the concentration of vanadium ions in the electrodes (graphite felts). The energy density is determined by the concentration of vanadium ions: the higher concentration, the higher energy density. The maximum concentration of electrolytes are limited by the solubility of $VOSO_4$, a starting electrolyte, and the stability of vanadium species. The solubility of V^{2+}, V^{3+} and VO^{2+}(4+) decreases with increase of the sulfate concentration due to the common-ion effect; but the stability and solubility of 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 V^{2+}, V^{3+}, and VO^{2+} electrolytes to increase the vanadium concentration. A novel electrochemical procedure has been developed to prepare a low acid and high vanadium (V^{3+}) concentration negative electrolytes. The obtained negative electrolyte contains a maximum 5 M vanadium with ~0.1 M H^+, and the positive electrolyte maximizes to ~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.

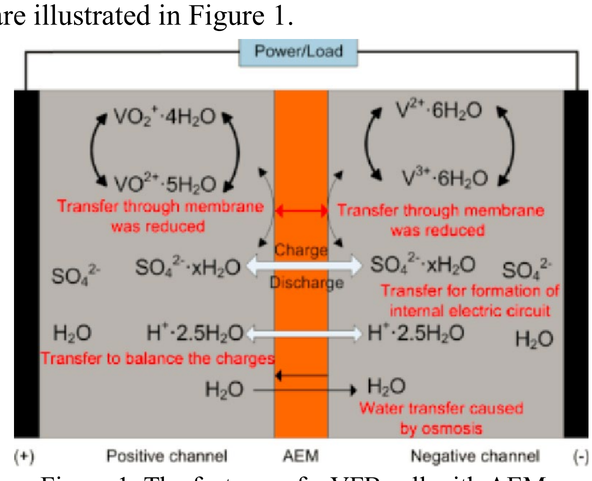


Figure 1. The features of a VFB cell with AEMs.

During the charge-discharge processes, vanadium redox reactions take place in negative and positive electrolytes; the bisulfate ions transport through AEM to form the internal electric circuit. Simultaneously, the sulfate and proton 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.

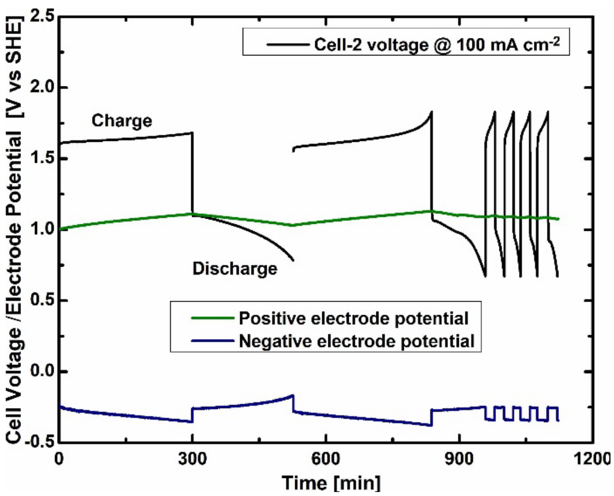


Figure 2. Charge-discharge cycles of VFB with an AEM and 3 M electrolytes in both sides.

<u>PROJECT STATUS/RESULTS</u>: 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 ionic conductivity of the AEMs and the negative electrolytes. Currently, novel catalysts are being developed for the redox reactions of vanadium ions at negative electrode to further improve the power density of the hight energy density VFBs.

Funding Source: Office of Naval Research

Contact: Yunfeng Zhai, yunfeng@hawaii.edu.

Last updated: November 2021

Appendix E: Advanced Materials

E1: Printable Photovoltaics

OBJECTIVE AND SIGNIFICANCE: The objective of this program 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 (e.g., polyamides or woven fabrics).

BACKGROUND: Crystalline silicon has been leading the PV market for over 20 years. These panels, found primarily on roof-tops and 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 more critical than performance. To this end, R&D efforts have 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 when needed.

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 raw chemical elements necessary for the synthesis of the solar absorber. These inks can be easily printed and cured to form thin film solar absorbers.

This project is currently focused on a multi-compound alloy ($CuInSe_2$, CISe), a material which meets the mechanical and weight requirements for light weight flexible PV. Recent results demonstrate that high-quality CISe solar absorbers can be achieved with this printing technology, leading to solar cells with power conversion efficiency over 8%. In addition, it has been demonstrated that additives, such as aluminum oxide, can be added to the molecular ink to passivate native defects in CISe during fabrication, yielding to efficiency as high as 11% (Septina, 2021). This technique is also being evaluated to synthesize other solar absorbers with promising properties for PV applications, including $Cu(In,Ga)Se_2$ and $Cu(In,Al,B)Se_2$.

This project has produced the following publication:

- 2021, W. Septina, C.P. Muzzillo, C.L. Perkins, A.C. Giovanelli, T. West, K.K. Ohtaki, H.A. Ishii, J.P. Bradley, K. Zhu, N. Gaillard, **In situ Al_2O_3 incorporation enhances the efficiency of $CuIn(S,Se)_2$ solar cells prepared from molecular-ink solutions**, Journal of Materials Chemistry A, Vol. 9, Issue 16, pp. 10419-10426.

Funding Source: Office of Naval Research

Contact: Nicolas Gaillard, ngaillar@hawaii.edu

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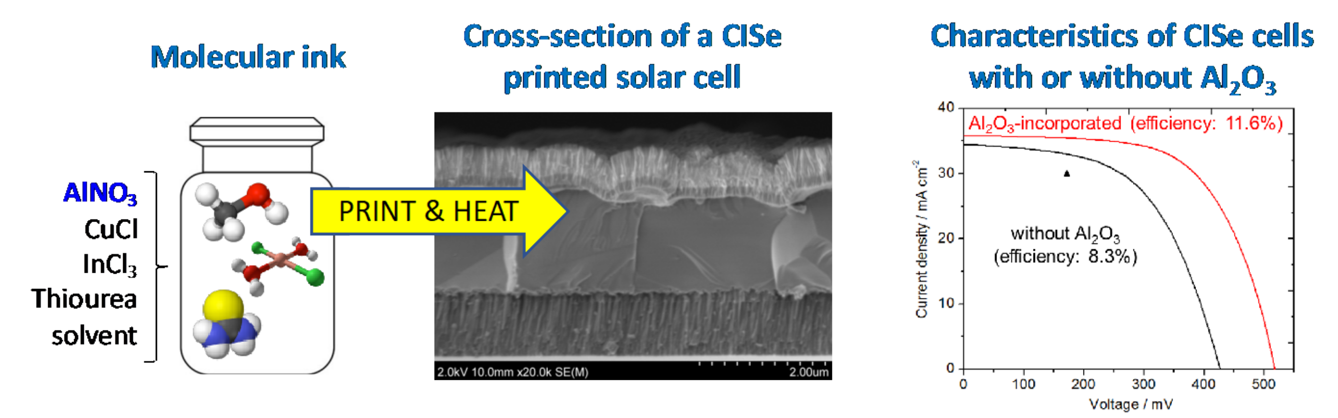

Hawai‘i Natural Energy Institute Research Highlights

Appendix E: Advanced Materials

E2: PHA Bioplastics and Hydrochar from Cellulosic Biomass

OBJECTIVE AND SIGNIFICANCE: This project aims to develop a biorefinery technology for producing 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 (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 investigated 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) (Figure 1). The biopolymer content in microbial cells reached about 60% dry mass. 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 ~48 lbs. of hydrochar (~$0.04/lb.) and ~11 lbs. of bioplastics (~$2/lb.). The technology can increase the value of raw biomass by more than ten 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, six research articles in peer-reviewed scientific journals, and three presentations in national and international conferences. Recent progress is described in the following publication:

- 2021, G. Mohan, et al., **Conversion of Pine Sawdust into Polyhydroxyalkanoate Bioplastics**, ACS Sustainable Chemistry & Engineering, Vol. 9, Issue 25, pp. 8383-8392.

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

Contact: Jian Yu, jianyu@hawaii.edu

Last Updated: November 2021

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

E3: Reversible Liquid Hydrogen Carriers Containing Magnesium Boranes

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to develop a commercially viable, two-way liquid hydrogen carrier (LOHCs) based on solutions of metal hydrides in heterocyclic LOHCs, that have a greater energy efficiency and lower delivery costs than existing hydrogen carriers and conventional compressed H_2 gas transport technology. The successful development of the liquid hydrogen carriers would support acceptance and expansion of hydrogen and fuel cell 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_2, 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 high density hydrogen storage materials, especially $Mg(BH_4)_2$, to the heterocyclic LOHC which can result in 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 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). The project is targeting the generation of two-way LOHCs by charging selected heterocyclic LOHCs with borohydrides. The project aims to identify the best heterocycle/hydride/catalyst combination in terms of rate, cycling capacity, and product selectivity with goal of maximizing energy efficiency of hydrogen storage and delivery.

PROJECT STATUS/RESULTS: The current HNEI research effort is focused on syntheses and characterization of ionic liquid (IL) and molten salts LOHCs containing borohydrides, with emphases on $Mg(BH_4)_2$. The immediate goal of the project is to validate the basic concept of significant hydrogen release from borohydride-LOHC combination.

Towards this effort, a variety of borohydride ionic liquids ($ILBH_4$) LOHCs materials have been synthesized. Characterization of the materials has been performed utilizing nuclear magnetic resonance spectroscopy (NMR), infrared vibrational spectroscopy (FTIR), and thermogravimetric analyses (TGA-DSC). The borohydride peaks in ATR-FTIR spectra in Figure 1 (on the following page), confirm the syntheses of the borohydride ionic liquids (($ILBH_4$); (A) 1-ethyl-3-methyl imidazolium borohydride, C_2mimBH_4; (B) 1-butyl-3-methyl midazolium borohydride, C_4mimBH_4; (C) 1-hexyl-3-methyl imidazolium borohydride, C_6mimBH_4; and (D) cholinium borohydride, $CholiniumBH_4$. The vibrational spectroscopy show the typical borohydride peaks in the 2200-2500 cm^{-1} and 1100-1400 cm^{-1} region (Figure 1a).

The synthesized borohydride ionic liquids were subsequently combined with $Mg(BH_4)_2$ and heat treated to 150-180°C in presence of Pd/Al_2O_3 catalyst, to determine the suitability of the $ILBH_4$-$Mg(BH_4)_2$ system for hydrogen release at moderate temperatures. The extent of dehydrogenation was followed by ^{11}B solution NMR. Products formation upon hydrogen release from the $ILBH_4$-$Mg(BH_4)_2$ samples can be confirmed by peaks at -29, -31 and -34 ppm (Figure 1b). Besides the syntheses and dehydrogenation of the $ILBH_4$-$Mg(BH_4)_2$ materials, we have also begun attempts to prepare higher hydrogen gravimetric density metal borohydride-heterocyclic LOHC materials. For example, we have prepared combinations of $Mg(BH_4)_2$/$LiBH_4$ and perhydro 9-ethyl carbazole. The mixtures were heat treated to 180-200°C in presence of minute amounts of tetrahydrofuran and Pd/Al_2O_3 catalyst. As seen in Figure 1c, new products are formed as a consequent of hydrogen release at these moderate temperatures. The boron peaks in the spectra are attributed to $MgB_{12}H_{12}$ (-16 ppm); $MgB_{10}H_{10}$ (-1 and -29 ppm) and unknown borane species (-21 and -24 ppm). The dehydrogenation of the borohydride LOHCs mixtures did not go to completion as evidenced by peaks of starting materials in NMR spectra. The preliminary results, are encouraging as they point towards plausibility of simultaneous hydrogen release from borohydrides and heterocyclic LOHC at moderate temperatures relevant for practical hydrogen delivery. In the future, we aim to improve the rates of dehydrogenation to ensure reactions go to completion, as well as, volumetrically quantify the amount of hydrogen released during the dehydrogenation reaction.

We will also perform high pressure calorimetry measurements to determine the extent to which the dehydrogenation thermodynamics of the borohydrides are altered upon mixing with LOHCs as well as elucidate the presence of thermal events associated with intermediary species and secondary products (observed in NMR spectra) formed 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.

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

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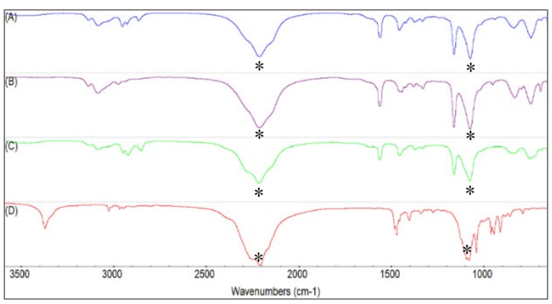
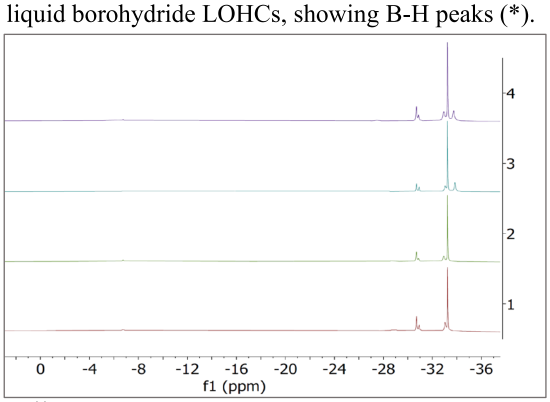
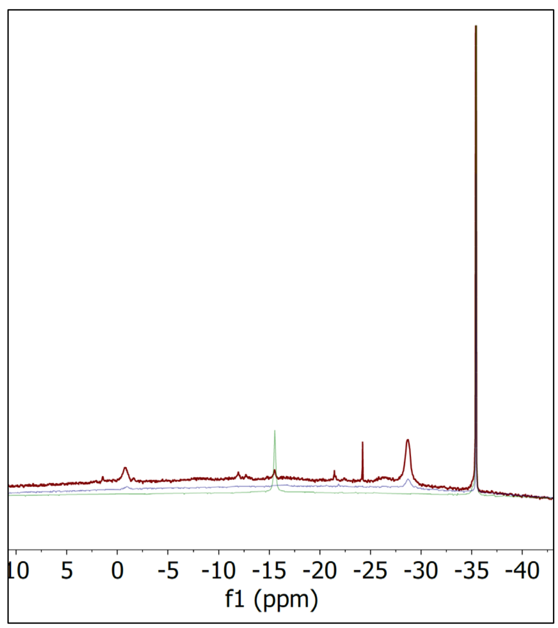


(a) ATR-FTIR spectra confirming syntheses of ionic liquid borohydride LOHCs, showing B-H peaks (*).



(b) [11]B Solution NMR of products of dehydrogenation of mixtures of ionic liquid borohydrides ($ILBH_4$) and $Mg(BH_4)_2$ at 150-200°C. Peaks at ~ -33 ppm due starting materials.



(c) [11]B Solution NMR of products of dehydrogenation of mixtures of $LiBH_4$ (green) /$Mg(BH_4)_2$ (red) and 9-ethyl carbazole using Pd catalyst at 150-200°C. Peaks at -33 to -35 ppm are due to unreacted metal borohydride starting materials. New product peaks are seen in 0 to -30 ppm range.

Figure 1. Characterizations of metal borohydrides and LOHC using NMR and FTIR. NMR spectra shows appearance of new species indicative of moderate temperature hydrogen release from the borohydrides.

E4: Magnesium Boride Etherates for Hydrogen Storage

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 (~400°C) and under high charging pressure (~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°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°C. This will be a significant improvement over the pre-project state of art (900 bar and 400ºC), as well as our previous year project achievement of 400 bar and 300ºC.

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: Our research effort is focused on the direct syntheses and characterization of modified MgB_2 with improved hydrogen uptake properties. The project continues to be guided by computational calculations from Lawrence Livermore National Laboratory (Figure 1). The molecular dynamic simulations suggest that additives e.g. THF or anthracene can modify the MgB_2 structure rendering it susceptible to hydrogen uptake at moderate conditions compared to pure MgB_2.

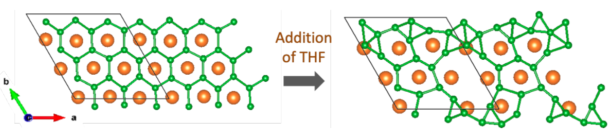


Figure 1. MD Simulations indicating strong coordination of THF to MgB_2 with plausible subsequent defect formation in MgB_2 structure.

To date, significant progress has been made towards improving the hydrogen storage properties of $MgB_2/Mg(BH_4)_2$ system (Figure 2). The bulk MgB_2 hydrogenation pressure has been reduced from 900 bar to 400 bar and temperatures from 400°C to 300°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°C. However, the hydrogenation is limited to the surface of the material with minimum hydrogen uptake into the bulk of the material.

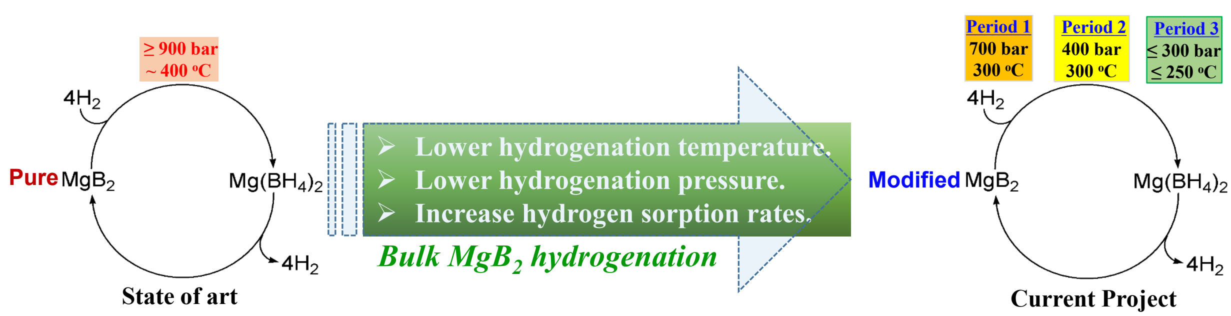


Figure 2. Progression of project efforts towards improving hydrogen storage properties of $MgB_2/Mg(BH_4)_2$ system.

Our research efforts towards improving the hydrogen uptake into the bulk of the material over the past year, did not result in significant improvement, at these desirable lower pressure and lower temperature conditions. A variety of characterizations were performed on the as-synthesized and hydrogenated MgB_2 materials (Figure 3). We have utilized: (a) X-ray absorption spectroscopy (XAS) to study the evolution of the boron or magnesium K-edge spectra of the as-synthesized and hydrogenated modified MgB_2 samples in attempts to correlate any trends of MgB_2 perturbation/destabilization to the extent of hydrogen uptake observed experimentally; (b) electron paramagnetic spectroscopy (EPR) to assist with determining if defects created through the ball milling and/or interaction of MgB_2 with modifiers, contributed to the higher hydrogen uptake observed in some of the modified MgB_2 samples; (c) nuclear magnetic resonance spectroscopy (NMR) to directly confirm the formation of $Mg(BH_4)_2$ from MgB_2 and; (d) scanning transmission electron microscopy (S)TEM to elucidate the microstructure and composition of the as-synthesized and hydrogenated MgB_2-graphene nanoplatelet samples.

The continuous improvement of the hydrogenation conditions of MgB_2 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_2 to $Mg(BH_4)_2$, to conditions relevant for onboard hydrogen storage.

A peer reviewed, journal cover article on discovery of additives for enhancing MgB_2 hydrogenation kinetics has resulted from this work. The final technical report was submitted to DOE-EERE.

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

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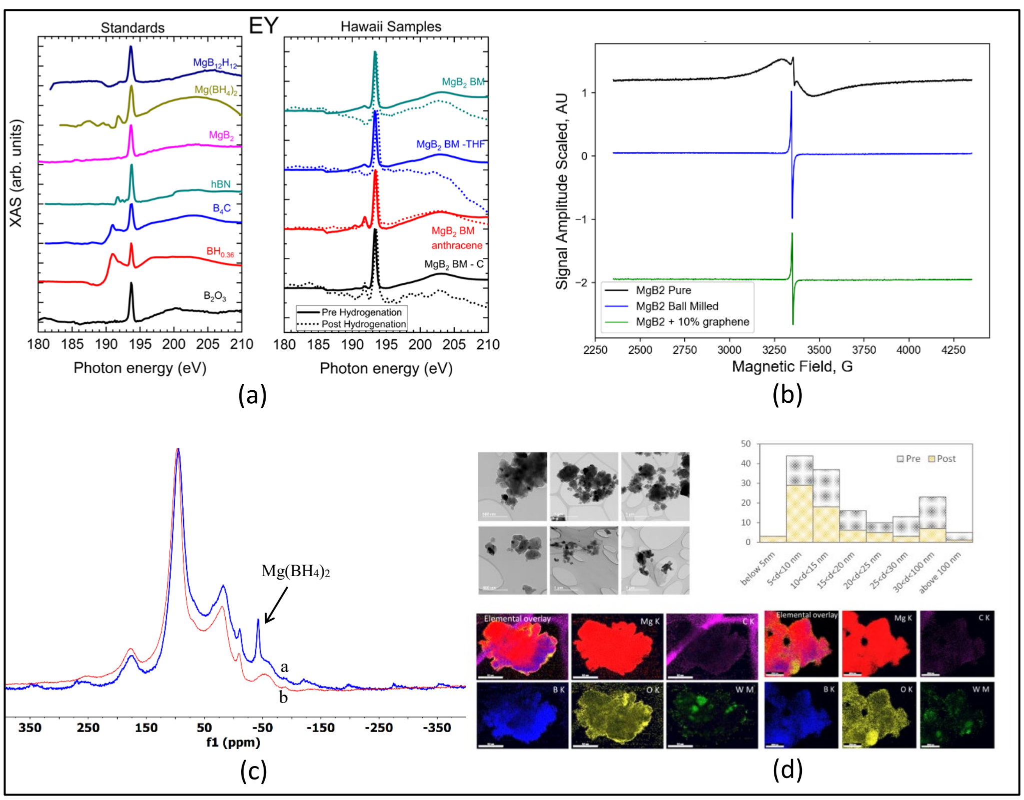

Figure 3. Typical characterizations of modified MgB_2 materials on project; (a) X-ray absorption spectroscopy (XAS), (b) Electron paramagnetic spectroscopy (EPR) (c) nuclear magnetic resonance spectroscopy (NMR) and (d) Scanning transmission electron microscopy (S)TEM.

ADDITIONAL PROJECT RELATED LINKS

TECHNICAL REPORTS:

1. 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.
2. 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.
3. 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:

1. 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 MgB2 to Mg(BH4)2 upon Mechanical Milling with THF, MgH2, and/or Mg**, ChemPhysChem, Vol. 20, pp. 1-5.

E5: Develop Advanced Magnesium Boride Hydrogen Storage Materials

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_2) to magnesium borohydride ($Mg(BH_4)_2$). 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_2/$Mg(BH_4)_2$) 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_2; 2) the reaction pathway of the reversible hydrogenation of MgB_2 to $Mg(BH_4)_2$; 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_2 to $Mg(BH_4)_2$ 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, and the National Renewable Energy Laboratory. HNEI’s role is focused on vibrational spectroscopy and calorimetry studies of the initial stages of H_2 uptake of modified MgB_2, as well as, syntheses of nano-sized MgB_2.

PROJECT STATUS/RESULTS: We prepared samples of magnesium boride modified with various additives including magnesium, graphene nanoplatelets and, magnesium and tetrahydrofuran (Mg+THF). The mechanically milled samples were heated to 250ºC and pressurized at 25-95 bar hydrogen in Parr Inc. high pressure rated reactors. The hydrogenation studies were performed in-order to determine the lower hydrogen uptake limits of the modified magnesium borides. The studies provide insights on the extent of hydrogen reaction with magnesium borides in the initial phase of hydrogenation. The extent of hydrogen uptake was studied by performing thermogravimetric analyses (TGA) on the

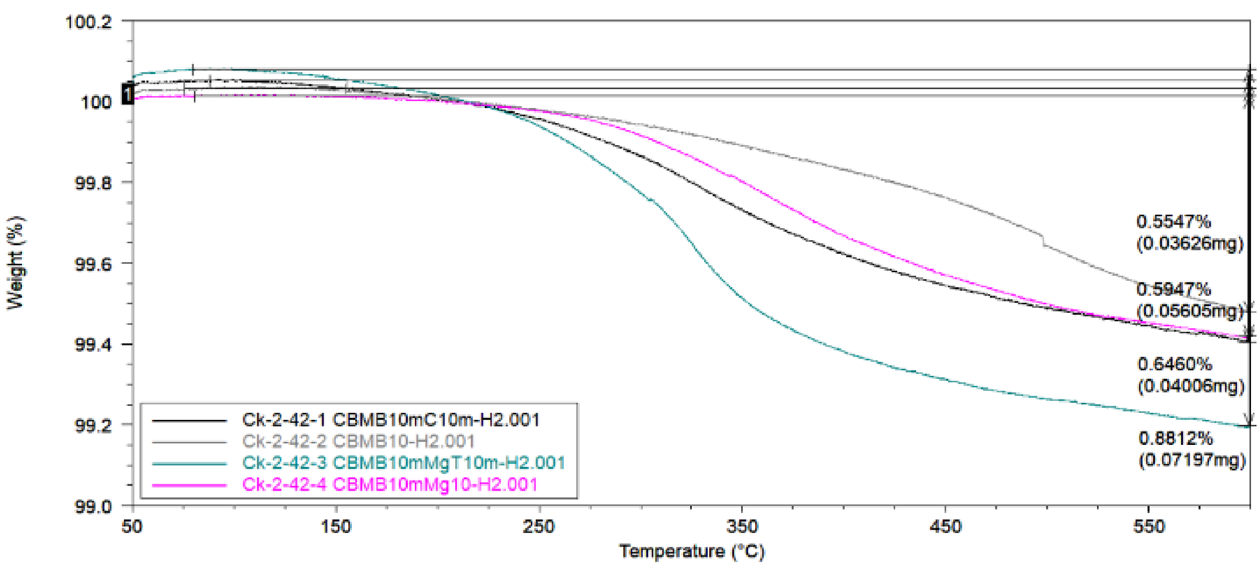

Figure 1. TGA profiles of hydrogenated modified magnesium borides undergoing dehydrogenation.

hydrogenated samples at a rate of 5ºC/min, under argon flow. The TGA profiles of the modified magnesium boride samples consistently showed mass loss of 0.5-1 wt% (Figure 1). The small amount of hydrogen release suggests the initial stage of hydrogen uptake in modified magnesium boride involve mostly surface hydrogen uptake. The results show for the first time hydrogen uptake in MgB_2 at pressures less than 100 bar, under thermal conditions.

Complementary effort on syntheses of nanosized thin films of magnesium boride using a combination of mechanical milling, heat treatment and/or sonication is underway. The thin films will be used to study the energetics of first steps of hydrogen adsorption on MgB_2 in collaboration with Prof. Brown at ME.

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

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Last Updated: November 2021

E6: Forward Osmosis Draw Solutions for Seawater Desalination

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to develop novel inorganic salts and ionic liquid based draw solutes for use as energy efficient, easily regenerable, high water flux, and low toxicity draw solutions in forward osmosis water purification. If successful, the novel draw solutes would lead to efficient sea water and brackish water purification using minimum amount of electrical energy compared to current state of art reverse osmosis or forward osmosis technologies.

BACKGROUND: Forward osmosis (FO) is a promising low pressure water purification technology with a low electrical energy use potential that is less hindered by the drawbacks of high hydraulic pressure of reverse osmosis (RO) water purification technology. The widespread commercialization of forward osmosis technology is challenged by a lack of practical, cost competitive draw solute materials with high osmotic pressure and low reverse draw solute diffusion that can be efficiently separated from the desalinated water. FO offers opportunities for higher water recovery efficiencies and lower membrane fouling. Forward osmosis, uses the osmotic pressure of a concentrated draw solution to pull water at low pressure with subsequent recovery of the fresh water from draw solute. A variety of draw solutes, including metal salts, organic compounds and synthetic materials (e.g. polymers, hydrogels) have been studied to date. Responsive solutes that can facilitate the separation of the draw solute from the desalinated water offer the greatest promise. For instance, the state of art ammonia/carbon dioxide thermally responsive draw solute is efficient in water recovery. However, the draw solute is hindered by the incomplete recovery of the ammonia, therefore the desalted water remains contaminated with residual ammonia. Hence, novel draw solutes are needed in order to fully realize the intrinsic benefits of forward osmosis water purification technology compared to state of art technologies.

Our research is focused on development of inorganic salts and ionic liquid based draw solutes with high desalination performance, and can be efficiently separated from water utilizing thermal, electrochemical, or magnetic draw solute recovery processes incorporating renewable energy sources or low grade energy sources, such as waste heat.

PROJECT STATUS/RESULTS: Our current efforts have been focused on assessment and evaluation of present literature and state of art draw solute materials used in forward osmosis water purification, to develop an in-depth understanding of the physio-chemical attributes of ideal draw solutes for forward osmosis technology. Furthermore, we have recently fabricated a forward osmosis system for characterizing the performance of draw solutions and forward osmosis membranes, Figure 1. The FO system is currently being tested and benchmarked using commercial draw solutes and membranes.

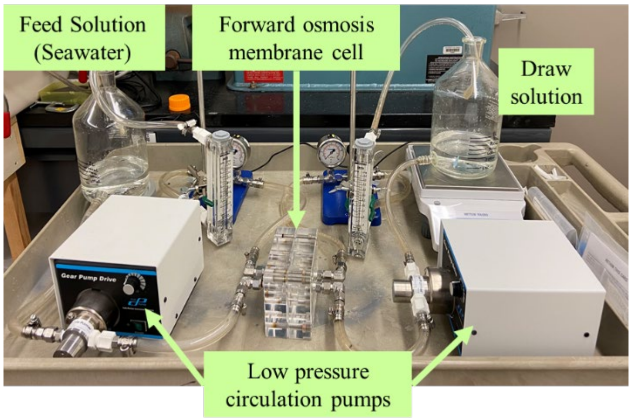


Figure 1. HNEI’s forward osmosis system.

In the future, state of art concentrated draw solutions will be prepared and tested for their potential to absorb high salinity sea water using the FO system. We will leverage our expertise in syntheses of novel ionic liquids and molten salts and materials characterization, to develop responsive ionic liquids and inorganic draw solutes for use in FO systems. The FO system will be used to evaluate and compare the performance of HNEI developed draw solutes against state of art draw solutions.

Funding Source: Office of Naval Research

Contact: Godwin Severa, severa@hawaii.edu

Last Updated: November 2021

F1: Seawater Air Conditioning Environmental Monitoring

OBJECTIVE AND SIGNIFICANCE: The objective of this research was to develop a thorough understanding of the baseline oceanographic conditions at the proposed site of the Honolulu Seawater Air Conditioning (SWAC) system. These data can be used to assess the potential environmental impacts of a seawater air conditioning system on Māmala Bay or other potential developments. The study provides insight into the nearshore oceanography of Oʻahu and how it differs from more oceanic locations nearby.

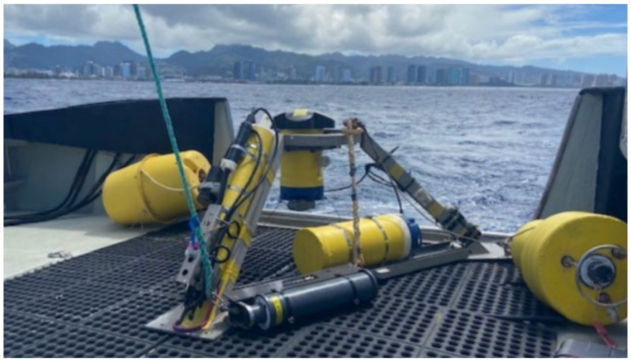
BACKGROUND: Seawater air conditioning is a type of renewable energy that utilizes deep, cold seawater as a nearly carbon-neutral source of air conditioning coolant. The proposed Honolulu SWAC system was designed to draw deep, cold seawater from 500 m and release effluent via diffuser at 100-140 m. Artificial upwelling of high-nutrient deep seawater could cause changes in local oceanography and food web dynamics.

At this time, the proposed Seawater Air Conditioning plant for Honolulu will not be constructed as previously planned, but the results of this monitoring effort are a valuable resource for the environmental assessment of any future industrial developments in the Māmala Bay area as well as for advances in the understanding of near-island oceanography in an oligotrophic ocean basin.

PROJECT STATUS/RESULTS: Sampling for the SWAC monitoring project was carried out from 2012-2020 and included shipboard CTD profiling and bottom mooring deployments. This long term sampling effort resulted in high quality time series oceanographic data for parameters including currents, temperature, chlorophyll-a, dissolved inorganic carbon, nutrients, dissolved oxygen, methane, nitrous oxide, and phytoplankton. These parameters were measured at the proposed intake (500 m) and effluent (100-140 m) locations.

Key results from the project include a better understanding of currents and of the depth and variability of the mixed layer within the bay and outside it. Bathymetric forcing from a canyon, along with island-scale internal tides, increased the variability in temperature, nutrient, and oxygen variability in the near bottom environment of Māmala Bay (Comfort, 2015). We observed a daily across-slope migration of the mesopelagic boundary community (Comfort, 2017). This community is an important part of the near-island food web, providing food for spinner dolphins and other predators, and we found that they would interact with effluent waters of a SWAC plant in their nighttime shallower habitat.

Data collection ended in December 2020. Final sample analyses are being completed in 2021. We are currently characterizing the onshore-offshore trends in phytoplankton which will help to better understand the shifts in phytoplankton communities driven by the island mass effect (the increase in productivity near islands in oligotrophic systems).



This project has produced the following publications:

- C.M. Comfort et al., The island mass effect drives shifts in *Prochlorococcus*:*Synechococcus* ratios from nearshore Oʻahu, Hawaiʻi to oceanic waters, In preparation.
- 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 Māmala Bay, Oʻahu, Hawaiʻi, 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 2021

F2: Building Energy Reduction in Transit-Oriented Development Areas

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 Oʻahu's light rail line. This helps Hawaiʻi 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 Hawaiʻi'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 Hawaiʻi'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, Hawaiʻi of approximately 20,000 ft².

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 Hawaiʻi. 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.

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.

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 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.

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.

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 Hawaiʻi 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 Hawaiʻi.

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

- 2021, W. Meguro, E.J. Glassman, **Evaluating Energy Targets and Efficiency Measures in Multifamily Subtropical Buildings through Automated Simulation**, Technology Architecture + Design, Vol. 5, Issue 1, pp. 82-95. (Open Access: **PDF**)
- 2021, W. Meguro, E.J. Glassman, **Designing Zero Energy Multifamily Buildings Informed by Simulation and Policy**, Presented at the Design + Architecture Hawaiʻi Event, September 30 - October 1.

Funding Source: Energy Systems Development Special Fund

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Last Updated: November 2021

F3: 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) Hawaiʻi. 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 Oʻahu buildings – two NAVFAC buildings located on the Joint Base Pearl Harbor Hickam and two stand-alone classrooms at the University of Hawaiʻi 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%.

Figure 1. UH Mānoa FROGs with LIDAR sensor (left) and exterior lighting fixtures (right).

The sensors and monitoring equipment collected data between January and July 2020. 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. The analyses of the data resulting from this work is available at in the project report: "**Adaptive Sensor-Based Lighting for Security Applications: Exploring Emerging Design Strategies**."

Funding Source: Office of Naval Research

Contact: Jim Maskrey, maskrey2@hawaii.edu

Last Updated: November 2021

F4: Healthy and Resilient Buildings Initiative

OBJECTIVE AND SIGNIFICANCE: The Healthy and Resilient Buildings Initiative ("Initiative") was developed by HNEI and introduced by the City and County of Honolulu, Hawaiʻi in the 4th Quarter of 2020 to offer free energy assessments vis-à-vis virtual energy audits to commercial building owners with revenue-grade smart meters. The objective was to provide an immediate pathway for relief to businesses from the coronavirus pandemic by using virtual energy audits to quickly identify operational energy savings from potential energy efficiency measures (EEMs) and indoor air quality improvements through potential increased air flow. The outcomes of each virtual energy audit were summarized in a report to participating building owners and outlined potential energy efficiency and resiliency measures to be further investigated for deployment.

BACKGROUND: The opportunity for energy efficiency savings in existing buildings is extremely large, considering that nearly two-thirds of the building area existing today will still exist in 2050 on a global level. At the federal level in the U.S., building retrofits are among the solutions chosen by the Biden Administration to pursue green jobs and climate change mitigation. These objectives are addressed under the proposed American Jobs Plan that includes building, preserving, and retrofitting more than two million homes and commercial buildings in the U.S. It is not clear, however, whether the retrofit of as many as a quarter of the commercial buildings in the U.S. can be achieved at the scale contemplated by the Biden policies without less expensive and quicker means to assess potential EEMs or indoor air quality improvements. The urgency for climate change mitigation may compel priority actions, such as strengthening the market pull for energy-efficiency innovations and demand-side policies.

PROJECT STATUS/RESULTS: The primary outcome of the Initiative was to establish the understanding that virtual energy audits are a step beyond benchmarking and could be used as an educational tool to motivate business owners to act on reducing energy use. Based on the virtual energy audit estimates of potential energy savings, business owners may wish to consider early replacement of less efficient equipment. For example, the four HVAC/cooling measures in the Honolulu case study account for 48-97% of the estimated energy savings of the ten audited buildings. While replacing HVAC equipment with more efficient models is an expensive retrofit, implementing the reschedule and set point changes on existing equipment accounts for 28-69% of the total estimated savings.

This project has produced the following publication:

- 2021, M.B. Glick, et al., **Analysis of Methodology for Scaling up Building Retrofits: Is There a Role for Virtual Energy Audits?—A First Step in Hawai'i, USA**, Energies, Vol. 14, Issue 18, Paper 5914. (Open Access: **PDF**)

Funding Source: Coronavirus Relief Fund established by the U.S. Congress under the CARES Act

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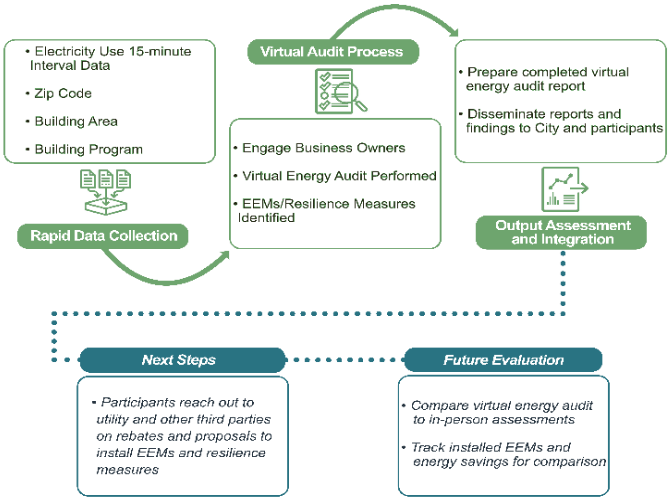
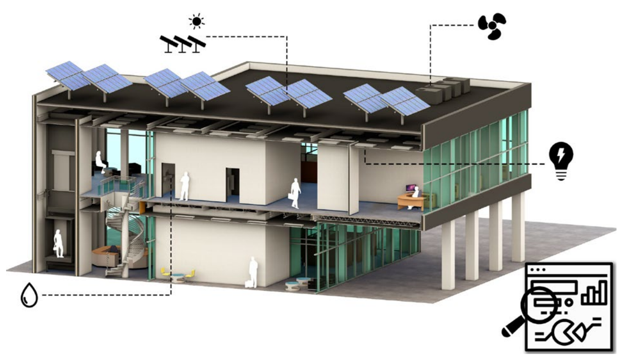
Last Updated: November 2021





G1: NELHA & MTA Hydrogen Stations and Fuel Cell Electric Buses

OBJECTIVE AND SIGNIFICANCE: HNEI has installed a 65kg/day hydrogen production and dispensing station on the Island of Hawaiʻi at the Natural Energy Laboratory Hawaiʻi 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 Hawaiʻi 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 Hawaiʻi's and the County of Hawaiʻi'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. HNEI's NELHA Hydrogen Station.

BACKGROUND: Development of hydrogen-based transportation systems requires infrastructure to produce, compress, store, and deliver the hydrogen; a means to dispense the fuel; and vehicles to use the hydrogen. The HNEI hydrogen station at NELHA has been designed to dispense hydrogen at 350 bar (5,000 psi). In place of ground-mounted 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 NELHA will be delivered to the MTA base yard in Hilo to support heavy-duty FCEBs operated by the MTA Hele-On public bus service. This concept is illustrated in Figure 2.

In additon 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 Hawaiʻi's Hawaiʻi Community College and the County of Hawaiʻi MTA to support 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: The site infrastructure, as well as the hydrogen production and compression systems equipment, have been installed at NELHA (Figure 3). In 2021, the station was fully commissioned by HNEI and Powertech, the equipment supplier.

Figure 3. HNEI Hydrogen Station

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 HydroPak compressor (Figure 4) compresses the hydrogen to 450 bar (6,600 psi).

Figure 4. HydroPac Compressor.

The system is powered by the Hawai‘i Electric Light Company (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 are certified 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 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.

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 7). 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 7. MTA Boost Compressor Fueling Post.

Hele-On 29-Passenger Fuel Cell Electric Bus: The Hele-On 29-passenger FCEB (Figure 8) 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. During this reporting period, the fuel cell power system was upgraded by replacing the original 30 kW Hydrogenics fuel cell with a new state-of-the-art 40 kW U.S. Hybrid fuel cell. During commissioning the fuel cell produced 46kW, a 15% improvement.

Figure 8. 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.

A 10 kW export power system (Figure 9) 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 9. Bus Export Power Unit.

Hele-On 19-Passenger Fuel Cell Electric Buses: Two 19-passenger FCEBs (Figure 10) were also acquired by the MTA from Hawai‘i Volanoes 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 provided by the County of Hawai‘i.

Figure 10. HAVO 19-Passenger FCEB.

Figure 11 is a conceptual design of the hydrogen fueling dispensing system located at the MTA base yard in Hilo which is comprised of repurposed, new equipment that was originally intended to support the two HAVO buses.

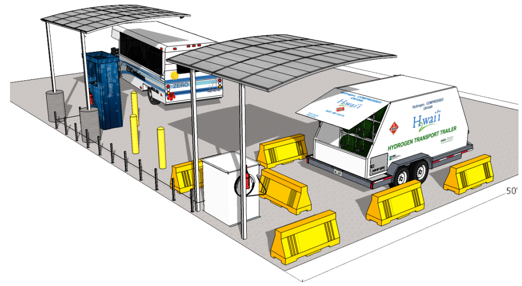


Figure 11. MTA Fueling Dispensing Station.

HNEI consulted with the MTA to select the location illustrated in Figure 12 for the hydrogen dispensing system. This single dispenser can support approximately 22 buses (illustrated) over a 6-hour period at a 16-minute fueling interval.

Figure 12. MTA Site with Fueling Dispenser.

This project has produced the following papers:

- 2020, A. Headley, et al., **Valuation and cost reduction of behind-the-meter hydrogen production in Hawai‘i**, MRS Energy & Sustainability, Vol. 7, Paper E26.
- 2020, M. Virji, et al., **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 2021

G2: Bidirectional EV Charging Demonstration Project

OBJECTIVE AND SIGNIFICANCE: The main objective of this project is to develop and evaluate the performance of novel algorithms to optimize the charge/discharge of shared fleet vehicles for energy cost minimization. Project experience and results will inform the university's 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 IKS Co., Ltd. (IKS) on technology development, test, and demonstration of advanced control of two bidirectional electric vehicle (EV) chargers (H-PCS) on the campus of UH Mānoa. In Figure 1, the two designated parking stalls (red rectangle) are located adjacent to the Bachman Annex 6 building (orange rectangle). The H-PCS was developed by IKS with support from Hitachi Limited as part of the earlier JUMPSmart Maui smart grid demonstration project, where HNEI was one of the partners.

Figure 1. Location of bidirectional EV chargers (H-PCS).

Two EVs procured by the project for this research will be used by designated university personnel in a car-sharing system accessed via a secure smartphone/web-based car scheduling application developed by the HNEI Grid***START*** team. Not only will the EVs be used for energy research and results dissemination, the project experience will allow the UH administration to evaluate the practical use of EVs as part of their vehicle fleet.

The novel H-PCS control algorithms developed by HNEI's Grid***START*** team will first ensure that the shared vehicles for UH personnel use are efficiently assigned and readily available for transport needs. Simultaneously, the autonomous controls will deliver ancillary power and energy services through intelligent EV charge and discharge commands, at times allowing the stored energy in the EV batteries to be strategically withdrawn to minimize the overall cost of energy supply to UH campus loads, and possibly support the operational needs of the local utility operator (i.e., Hawaiian Electric Company) through the supply of grid ancillary services in return for financial compensation.

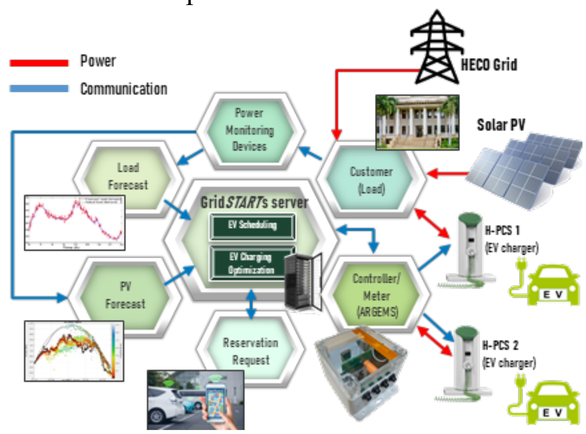

Figure 2. Functional system diagram

The novel algorithms also incorporate data fed from state of the art in-house developed forecasts of campus building demand along with forecasts of on-campus solar PV power production, thus maximizing the use of renewable energy as the preferred source for EV charging and supply to building loads, while minimizing costly energy purchases from the grid.

PROJECT STATUS/RESULTS: HNEI has purchased two EVs and has completed the field installation of the two H-PCS provided on loan by IKS for the duration of the two-year demonstration project. The two bidirectional EV chargers are presently being commissioned by HNEI and IKS engineers. Under a Standard Interconnection Agreement with Hawaiian Electric Company, both H-PCS are approved to operate in parallel with the utility grid as the first bidirectional EV chargers in use on O‘ahu. The custom web-based reservation software integrated with novel control algorithms to optimize the EV charge/discharge schedules are under test.

Funding Source: Office of Naval Research

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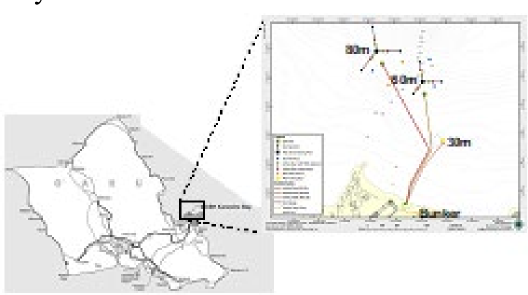
Last Updated: November 2021

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

OBJECTIVE AND SIGNIFICANCE: Wave energy has 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 advance development of wave energy conversion (WEC) devices and related technologies. For this reason, the U.S. Navy established the Wave Energy Test Site (WETS) in the waters off Marine Corps Base Hawaiʻi (shown below) as the United States' 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 (OWC) devices to a peak power of 1 MW. HNEI provides key research support to this national effort in the form of environmental monitoring, independent WEC device performance analysis, and critical marine logistical support. The results achieved at WETS have far reaching impacts in terms of advancing wave energy globally.



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 during their WEC deployments at the site.

In Summer 2021, NAVFAC granted HNEI an additional $6 million to continue this core support to WETS, and to expand research related to smaller-scale WECs for offshore, non-grid-connected applications of wave energy. This will include: 1) an examination of the potential for existing WETS infrastructure to support the creation of an offshore test and demonstration node, including subsea power storage as well as communications and power interfaces that would allow small WECs to power applications such as autonomous undersea vehicle (AUV) recharge and data upload, environmental sensing systems, ocean observation, and navigation; 2) design of an AUV docking and charging station for WETS; 3) development of a power generation and management system for a floating OWC device of UH design, for applications such as ocean observation, navigation, and AUV recharge; 4) advancement of a novel breakwater system with integrated OWC power generation; and 5) concept development of a nearshore, small-scale, rapidly deployable WEC for power generation and/or seawater desalination. Wave energy has enormous potential to supply persistent power to these non-grid-connected applications, as well as to aquaculture, at-sea mineral scavenging, and providing renewable power to remote or island communities.

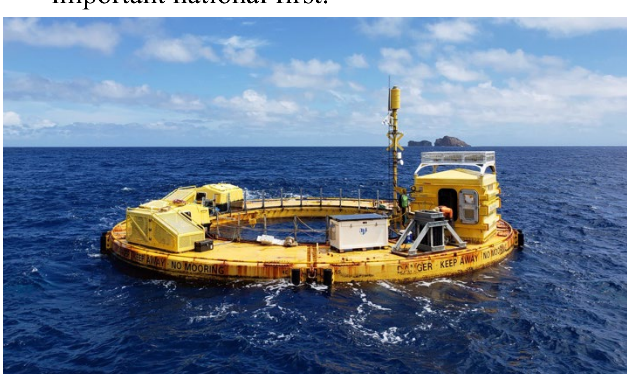
PROJECT STATUS/RESULTS: Since mid-2015, the following major activities have occurred at WETS, with HNEI in both supporting and leading roles. Photos depicting the events are provided under each bullet:

- Northwest Energy Innovations (NWEI) deployed Azura device at 30m berth Jun 2015 to Dec 2016.

- Sound and Sea Technology deployed Fred. Olsen Lifesaver at 60m berth – Mar 2016 to Apr 2017. This project was not grid-connected.

- 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 – Feb to Aug 2018.

- 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 – Oct 2018 to Mar 2019. This use of wave energy to power an offshore sensing suite was an important national first.



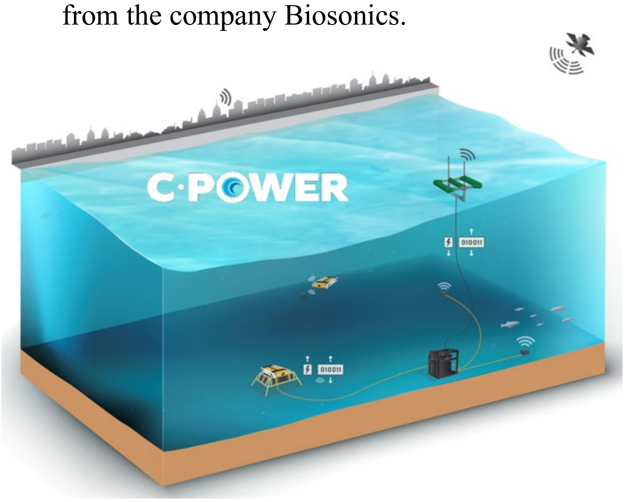
- Completion of site-dedicated support vessel Kupaʻa , by research partner Sea Engineering, Inc. – November 2019. This vessel adds significantly to our ability to perform various functions at WETS.

- HNEI led a major redesign and reinstallation effort for the WETS deep berth moorings. 60m berth reinstalled in May/Jun 2019, 80m berth repairs held, subject to WEC developer demand.

Several activities are planned in the coming year:

1) Deployment of the Oscilla Power (Seattle) Triton-C community-scale WEC at the 30m berth. This device arrived in Hawai'i in October 2021, and will be deployed to WETS upon completion of site upgrades, including the installation of new anchors and a new electrical/data junction box. Pending weather availability for these operations and for the deployment itself, the Triton-C should deploy in early spring 2022.

2) 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.



3) Deployment of the Ocean Energy (Ireland) OE35 WEC at the 60m berth. This device has been in Hawai'i since December 2019, but must undergo repairs in drydock prior to deployment. These repairs have been delayed by various issues, including travel restrictions related to COVID-19.

Looking ahead, we expect WEC deployments from C-Power (a larger device called StingRay), Northwest Energy Innovations (a much larger version of Azura), and Oregon-based Aquaharmonics – in the 2023-2025 timeframe.

Funding Sources: Naval Facilities Engineering Command, Expeditionary Warfare Center; U.S. Department of Energy

Contact: Patrick Cross, pscross@hawaii.edu

Last Updated: November 2021

H2: The Hawaiʻi Wave Surge Energy Converter (HAWSEC)

OBJECTIVE AND SIGNIFICANCE: The objective of the Hawaiʻi Wave Surge Energy Converter (HAWSEC) project is to mature a WEC concept developed by the HNEI led team, that could ultimately produce cost-effective renewably generated electricity for coastal communities. The project 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 Hawaiʻi, 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 Hawaiʻi, since 2010, with funds from both the U.S. Department of Energy (DOE) and the U.S. Navy (Naval Facilities Engineering Command – NAVFAC). 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. 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. 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. Rendering of the HNEI HAWSEC system.

HAWSEC development is proceeding 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 Oʻahu;
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 nominally three-year project was initated in August 2020. Task 1 numerical modeling is complete, and the smaller-scale flap system has been designed and fabricated. A hydraulic bench test setup has been largely procured and will be set up in our lab on the UH campus in late 2021. Nearshore testing of the flap in local waters (at Makai Research Pier) has been approved and will also take place in late 2021.

Substantial procurement challenges – some associated with COVID-related supply chain issues – have delayed this timeline considerably, and we now expect to be testing in the wave basin at Oregon State University in March 2022. Results from this testing will be crucial in validating numerical models at the smaller scale and scaling these results up to a larger-scale device for subsequent testing. The first budget period in the project will conclude with a final design for the larger-scale WEC, which will be built and tested in the second budget period, subject to approval by DOE.

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

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Last Updated: November 2021

I1: Asia Pacific Regional Energy System Assessment (APRESA)

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, regulation, technology options, demonstrations, 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 World Bank (WB), Asian Development Bank (ADB), U.S. Agency for International Development (USAID), 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, Papua New Guinea and the Philippines, with new engagements under development in various Pacific Island countries. 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.

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. Many of these are also described in more detail in separate project summaries included in this Appendix.

Thailand: Biomass Gasification Demonstration
With APRESA funding, HNEI contracted 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, and develop gasifier system control strategies for interfacing with the intermittency of other micro-grid components.

Biochar Production from Rice Husk and Plastics
An evaluation of mixed waste pyrolysis concluded with the publication of the manuscript: "**Investigation of Biochar Production from Copyrolysis of Rice Husk and Plastic**" in the journal ACS Omega. APRESA supported the exchange visit of Dr. Ketwalee Kositkanawuth from the King Mongkut's University of Thailand, Thonbury at HNEI and the evaluation of the biocarbon products detailed in the journal article.

Postdoctoral Training in Sustainable Aviation Fuel
APRESA funds have supported Dr. Quang Vu Bach's participation 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.

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's Grid***START*** team and EGAT built and calibrated a high-fidelity production cost model of the Thai power grid in PLEXOS. In March 2021, a multi-day remote workshop was held for EGAT, focusing on model updates, tuning and calibration. Time series photovoltaic (PV) and wind data sets for all existing RE and future high penetration RE cases were developed and analyzed with multiple distributed PV scenario cases. Application of this Thai power grid model continues including analysis of the need for more flexible grid assets and measures to meet this need. This work, described in more detail in Appendix I2, extends and expands the collaborative work amongst HNEI and EGAT.

Provincial Electricity Authority of Thailand (PEA) Collaboration
HNEI's Grid***START*** team developed a capacity building program focused on renewable energy integration and smart grid technologies development and application for engineers from the Provincial Electricity Authority of Thailand (PEA), the Thai distribution grid operator responsible for electricity supply to the entirety of Thailand, except for the Bangkok metropolis and two adjoining provinces (Thailand has 77 total provinces). Initiated in Spring 2020, the internship program was designed to accept two classes of six PEA engineers annually, participating in an eight-week curriculum of combined lectures (40 hours) and team oriented deep emersion in custom "mini-project" research, development, and test endeavors tailored to the learning needs of working utility engineers. A renewable energy integration and smart grid technologies series of lectures with emphasis on energy distribution system applications was developed and delivered to the PEA engineers. The first PEA intern class was received at HNEI from March to May 2020. However, due to COVID-19 travel restrictions, the second intern class was postponed and bifurcated into: (1) a five-day online lecture component conducted remotely in May 2021; and (2) an in-person lecture and mini-project component from October to December 2021. For the in-person component currently underway at HNEI in Honolulu, Hawai'i, the intern class was split into two teams, each focused on one of two mini-project topics: (1) ARGEMS application development: Distribution Secondary Fault Detection and Location; and (2) Bidirectional EV Charging Control Optimization. This work is described in more detail in Appendix I9.

Technical Support for Development of BESS Technical Standards for Thailand
The support objective of this project was to provide technical assistance to Thailand's Office of Energy

Regulatory Commission (OERC) in its ultimate adoption of codes and regulations for battery energy storage system (BESS) applications in Thailand. Through leveraged partial funding by USAID Clean Power Asia (CPA), HNEI has provided expert advice to OERC and Thai stakeholders, culminating in the delivery of a comprehensive guide and roadmap for developing BESS technical codes and standards for Thai regulatory action. Following the first Stakeholder Focus Group held in August 2020, a Final Stakeholder Consultation Workshop was held in Bangkok on February 18, 2021. HNEI presented online the final draft of the BESS technical standards report to OERC, with Thai electric utilities and numerous energy sector stakeholders in attendance. Stakeholder feedback was incorporated into the final deliverable "*Guidelines for Developing BESS Technical Standards in Thailand*," which was submitted to USAID CPA on March 29, 2021, for delivery to OERC. This work is described in more detail in Appendix I10.

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

The MOU establishes a framework for multi-year collaboration amongst HNEI and Chula engineering faculty on a range of activities exploring approaches, methodologies, tools, techniques, systems, and policies that lead to enhanced resilience and energy reliability while enabling a clean energy transition through grid modernization and smart grid initiatives. Collaborative endeavors include the following two projects.

Thailand Regional Solar PV Forecasting Project: The HNEI solar forecasting system combines information derived from numerical weather prediction (NWP), satellite images, and ground based instruments to monitor current regional irradiance conditions in near real-time and predict upcoming irradiance conditions and resulting PV power production, from minutes to days ahead. HNEI's Grid***START*** team setup a new test domain for its solar forecasting system to evaluate its application in Thailand. Utilizing archived Himawari-8 satelite images, a month of 6-hour ahead irradiance forecasts were generated for over 30 test sites in Thailand. At each site, ground-based observations of hourly insolation were provided. To visualize the results, a regional aggregate dashbord was built using web-based tools, which can be found at: http://128.171.156.27:5100/sitesforecast/. This work is described in more detail in Appendix I11.

Chulalongkorn Smart Campus Project – ARGEMS: To build joint research and development capacity in the area of grid modernization and smart grid initiatives, HNEI is field deploying multiple devices of its Advanced Real-time Grid Energy Monitor System for integration with other smart grid technologies in Chula's Smart Campus Project. Two ARGEMS devices have been shipped to Chula. The first device has been operating in a lab setting for over a year, and the second device is ready for installation on a building transformer. Other devices have been prepared for final configuration and shipment. This work is described in more detail in Appendix I7.

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. With rapidly growing industrialization and modernization of the economy, energy demand is predicted to increase by over 10 percent annually during 2016-2020 and by eight percent per annum during 2021-2030 resulting in a four-fold increase in total electricity demand by 2030 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 all the 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. 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, 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. This work is described in more detail in Appendix I3.

Renewable Energy Integration Support in Vietnam
The USAID 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 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.

HNEI's Grid***START*** team contributed to V-LEEP's report to MOIT/EREA on a new methodology roadmap to update the historical PDP process and to incorporate international best practices for planning for higher levels of variable renewable energy. Based on the results of this assessment, MOIT/EREA adopted V-LEEP's recommendations on a new process and methods, including the use of advanced grid simulation tools for PDP-8 analyses. To implement this shift in PDP-8 analytical approach and methodology, MOIT/EREA established a Modeling Working Group (MWG) to conduct production cost analysis for the development of PDP-8. V-LEEP, together with HNEI and NREL, delivered two technical trainings in Hanoi for the MWG and other relevant stakeholders on the application of advanced modeling tools and analytics in long-term planning. In March 2021, Deloitte delivered to MOIT/EREA a technical report, *Impact Analysis of Integrating Significant Renewable Energy in Vietnam's Power Sector: A PLEXOS-based Analysis of Long-Term Power Development Planning*, that provides feedback for MWG generation and transmission planners to optimize the PDP-8 using the least-regret approach. This work is described in more detail in Appendix I14.

Technical Interconnection Requirements for Solar and Wind Projects in Laos
Starting in 2018, HNEI, in a partnership with USAID Clean Power Asia (CPA), drafted interconnection grid codes and supported power purchase agreement (PPA) structure and terms development for Laos' first market-based competitive solar pilot auction. Based on this work, Électricité du Laos (EDL), the Laos grid operator, requested extended support from HNEI to develop interconnection grid codes for distributed PV and utility-scale solar and wind projects, a foundational need to enable uptake of solar and wind resources into the Laos power grid. HNEI's Grid***START*** team commenced work in 2020 on the development of two key deliverables: (1) *Électricité du Laos Distributed Solar Photovoltaic Generating Facility Interconnection Standards* (Dec 2020); and (2) *Électricité du Laos Inverter-based Generating Facility Transmission Interconnection Standards* (Jan 2021). These deliverables were submitted and presented jointly by HNEI and USAID CPA to EDL and the Lao Ministry of Energy and Mines (MEM) in March 2021. This work is described in more detail in Appendix I8.

Energy Secure Philippines (ESP) – Philippines' Net-Metering Framework; Regulatory Framework for BESS
In 2019, HNEI's Grid***START*** team provided technical and capacity building support in collaboration with USAID Clean Power Asia to assist the Philippines Department of Energy (PDOE) to prepare and present its Department Circular (DC) for "*Promulgating Policies to Enhance Customers' Participation in the Philippines' Net-Metering Framework*." In 2020, PDOE issued a new Net-Metering Policy which, while maintaining the 100 kW limit on system capacity, removed the Distribution Impact Study fee imposed by distribution utilities on Net-Metering applicants. HNEI Grid***START*** continued throughout 2020 to provide online capacity building webinars offering

in-depth training to Philippine energy regulators, administrators, energy stakeholders, and particularly the implementing staff of the numerous Philippine distribution utilities charged with Net-Metering program execution and PV system interconnections. Following the new policy enactment, the participation rate in the Net-Metering Program has increased by almost 15%.

In 2021, HNEI is supporting the activities of the new USAID Energy Secure Philippines (ESP) Program and the Philippines Energy Regulatory Commission (ERC) to advance inclusive economic growth and resilient energy sector development through the following two project endeavors: (1) the enactment of new net energy metering (NEM) rules tailored for their numerous small island grid systems; and (2) the establishment of a regulatory framework for battery energy storage systems (BESS) adoption in the Philippines. This work will be described in more detail in a subsequent report.

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 have conducted three AIMS studies to date. The latest development in the study, AIMS III, began in 2019 and builds upon the foundational work of the previous two studies. It aims to evaluate ASEAN power market integration through the grid connection of renewable energy and power trade. HNEI's Grid***START*** team is providing technical assistance as a core member of the Technical Review Group (TRG) for the AIMS III effort. The TRG, comprised of a core and secondary group of international experts, is tasked with performing reviews and providing guidance on the scope, data needs, assumptions, analyses and results of AIMS III. The AIMS III work is divided into three phases. Phase 1, Capacity Expansion Planning, and Phase 2, Grid Performance Analysis, are both complete. HNEI is presently engaged in scoping discussions at the request of the ASEAN Center for Energy (ACE), an intergovernmental organization within the ASEAN structure representing the 10 ASEAN Member States' (AMS) interests in the energy sector, for continued technical support of Phase 3, Multilateral Market Analysis, which is yet to start. This work is described in more detail in Appendix I6.

ASEAN Centre for Energy (ACE) Capacity Building
HNEI's Grid***START*** team is delivering training at the request of the Jakarta, Indonesia based ASEAN Centre for Energy (ACE), an intergovernmental organization representing energy sector interests of the ten ASEAN Member States (AMS). The capacity building initiative endeavors to build the knowledge base and capability of ACE planning/engineering staff in the advanced analytics needed for effective renewable energy integration analysis, and ultimate power grid modernization and optimization in ASEAN countries. In February 2020, in-person training was provided at ACE headquarters in Jakarta on the need for, value, tools, and methodologies of production cost modeling and analytics. Follow-on extended training for ACE personnel at HNEI in Honolulu was scheduled, but postponed due to COVID-19 travel restrictions. This training will enhance ACE's close work with energy authorities/ministries/utilities 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 sustainable and environmentally friendly growth. In anticipation of reduced restrictions on travel, discussions are again underway with ACE to resume hands-on capacity building endeavors in Jakarta and/or Hawaiʻi.

Funding Source: Office of Naval Research

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Last Updated: November 2021

Hawai‘i Natural Energy Institute Research Highlights

Appendix I: International

I2: EGAT Renewable Integration Study

<u>Objective and Significance</u>: HNEI 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 grid simulation tools.

<u>Background</u>: 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.

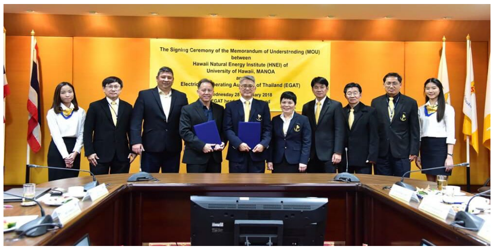

Figure 1. HNEI-EGAT MOU signing ceremony in 2018.

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, empowering EGAT engineers to perform such analyses on its own going forward.

High levels of customer-sited distributed PV pose grid challenges due to its intermittency and variability and the limited flexibility of legacy power systems to respond to and balance resulting system net load. With high levels of RE, many conventional generation resources are shut down or dispatched at minimum operating levels to “make room” for the new RE generation, with remaining online units needing to ramp more quickly and frequently over a wider operating range to counter the variability and uncertainty of RE production. The cost of dispatched generation may also increase due to less efficient operation and the need for increased operating reserves. 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.

<u>Project Status/Results</u>: HNEI Grid***START*** and EGAT built and calibrated a high-fidelity production cost model of the Thai power grid in PLEXOS. In March 2021, HNEI Grid***START*** held a multi-day remote workshop with EGAT focused on model updates, tuning and calibration. The PLEXOS model includes seven nodes – each node representing a region of Thailand with inter-nodal transmission transfer limits modeled.

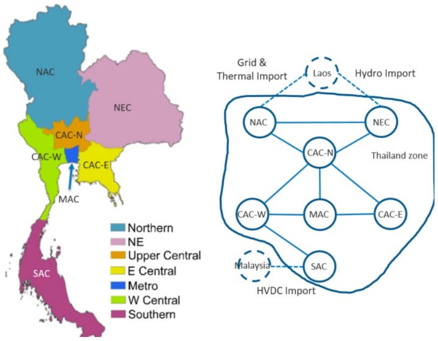

Figure 2. Thailand PLEXOS “bubble model” topology.

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 were completed with conditions of operational concern identified, including excess energy production potential during low load periods. Modeling continues to assess flexibility counter-measures to grid impacts of high RE.

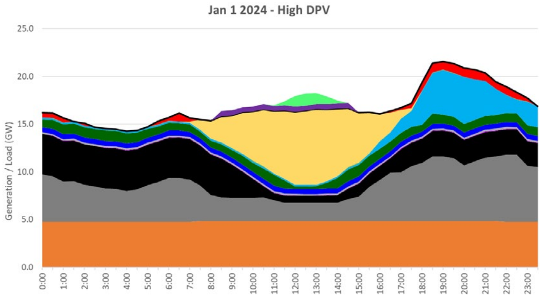

Figure 3. Thailand 2024 low system load day with high distributed PV, with distributed PV (yellow) and excess PV production (green).

Funding Source: Office of Naval Research

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Last Updated: November 2021

I3: Vietnam: Mapping of Renewable Energy Sector Innovation System

OBJECTIVE AND SIGNIFICANCE: Under funding of its Asia Pacific Regional Energy System Assessment (APRESA) program, 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 2022.

PROJECT STATUS/RESULTS: By November of 2021, NISTPASS completed a second round of interviews of stakeholders in the renewable energy sector in Vietnam, focusing on solar and wind energies. The interviewed stakeholders in two rounds of interviews, were divided into 4 groups: (i) government agencies; (ii) academic organizations, such as R&D organization and universities; (iii) companies: and (iv) intermediary organizations.

The interviews have yielded 21 overall trends and findings ranging to opportunities in the supply side of the sector innovation system to the impacts of environmental factors and the COVID-19 pandemic.

Funding Source: Office of Naval Research

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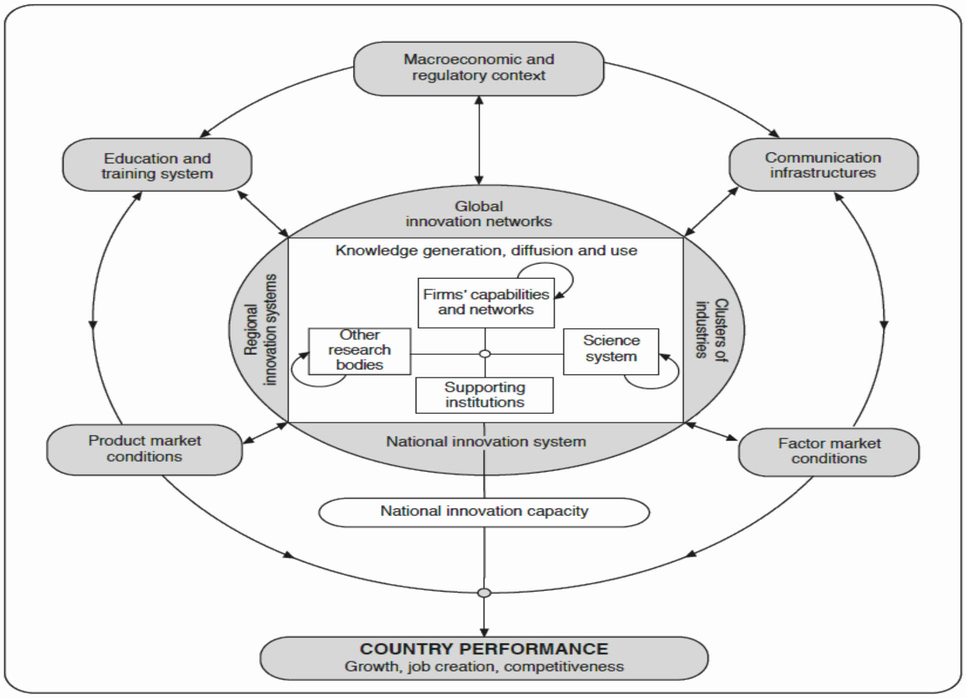
Last Updated: November 2021



I4: Development and Verification of AI-Based Microgrid Platform and Business Model

Objective and Significance: The goal of this project is to demonstrate the capabilities of an advanced control system using artificial intelligence (AI) to optimize energy management of a distributed solar and energy storage based microgrid to reduce costs, and improve resilience of the seawater distribution system at the Hawaiʻi Ocean Energy, Science & Technology (HOST) Park. The microgrid control system has been designed with the potential capability to provide energy management across 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 demonstration site is in a section of the Park that 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 Hawaiʻi (NELHA), an agency of the State of Hawaiʻi. 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 Hawaiʻi 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 an AI microgrid that includes photovoltaic panels and battery energy storage systems 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. Construction, delayed as a result of COVID-19, has resumed with a revised estimated October 2022 date for the microgrid to be operational.

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

- 2021, W-H. Park, H. Abunima, M.B. Glick, Y-S. Kim, **Energy Curtailment Scheduling MILP Formulation for an Islanded Microgrid with High Penetration of Renewable Energy**, Energies, Vol. 14, Issue 19, Paper 6038. (Open Access: **PDF**)
- 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**)
- 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**)

Funding Source: KETEP (subcontract with Encored, Inc.)

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Last Updated: November 2021

Hawaiʻi Natural Energy Institute Research Highlights

Appendix I: International

I5: U.S. India Collaborative for Smart Distribution with Storage (UI-ASSIST)

<u>Objective and Significance</u>: The project objective is to foster international collaboration around smart grids, particularly distribution systems and microgrids with solar photovoltaics (PV) and energy storage. The Hawaiʻi Natural Energy Institute (HNEI) at the University of Hawaiʻi is among an esteemed group of U.S. institutions, including Washington State University (WSU), Massachusetts Institute of Technology, 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 involved in this project. This project is an important opportunity to highlight Hawaiʻi's challenges and solutions at the forefront of renewable energy (RE) integration, while inviting input from international leaders in smart grid research and technology development.

<u>Background</u>: HNEI's work addresses the following objectives within the larger project:

- 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);
- 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;
- Provide live updates of multi-horizon PV forecasts 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
- Provide outreach and workforce development addressing smart grid technologies and RE grid integration.

<u>Project Status/Results</u>: As of year four of the six-year project, UH researchers and postdoctoral fellows have:

- Adapted and tested Hawaiʻi 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;
- Gave numerous webinars and presentations including at the IEEE Power and Energy Society panel; and
- Supported K-12 education by advising two high school students on the research projects related to the RE grid integration and presenting an exhibit attended by approximately 1,000 Hawaiʻi K-12 students (Figure 2).

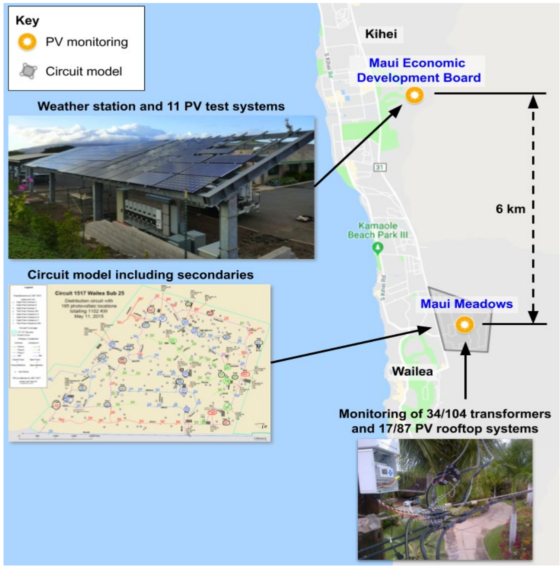

Figure 1. Overview of HNEI's data and models from the area of South Kīhei, Maui.

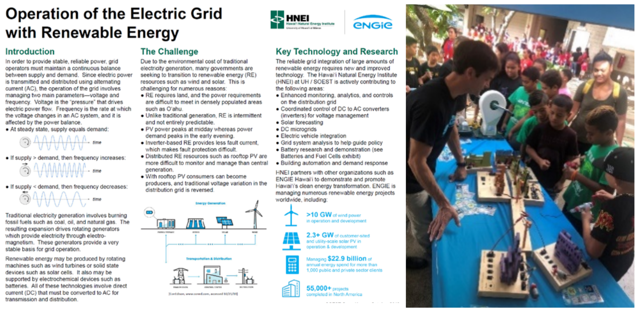

Figure 2. Poster and interactive display presented to K-12 students at the 2019 SOEST Open House at UH Mānoa.

Funding Source: U.S. Department of Energy (subaward from Washington State University); Energy Systems Development Special Fund

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Last Updated: November 2021

Hawaiʻi Natural Energy Institute Research Highlights

Appendix I: International

I6: ASEAN Interconnection Masterplan Study (AIMS) III Support

OBJECTIVE AND SIGNIFICANCE: Under HNEI's Asia Pacific Regional Energy System Assessment (APRESA) award from the Office of Naval Research, HNEI's Grid***START*** team is providing technical assistance as a core member of the Technical Review Group (TRG) for the ASEAN Interconnection Masterplan Study (AIMS) III effort. The TRG is comprised of international experts tasked with performing reviews and providing guidance on the scope, data needs, assumptions, analyses and results of AIMS III.

BACKGROUND: 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 three AIMS studies to date. The first study, AIMS I, was completed in 2003 and proposed a comprehensive power transmission network. The second study, AIMS II, completed in 2010, addressed the viability of generic cross-border links based on bilateral agreements.

The latest development in this phased study, AIMS III, began in 2019 and builds upon the foundational work of the previous two studies. It aims to evaluate ASEAN power market integration through the grid connection of renewable energy and cross-border power trade amongst the 10 ASEAN Member States' (AMS). Specifically, AIMS III seeks to address: rapid changes in the economic landscape and electricity supply; renewable energy integration (including the ASEAN RE target of 23% of the energy mix by 2025); benefits and challenges of higher variable renewable energy (VRE) integration; adoption of new emerging technologies; and the sustainability and advancement of multilateral power trade.

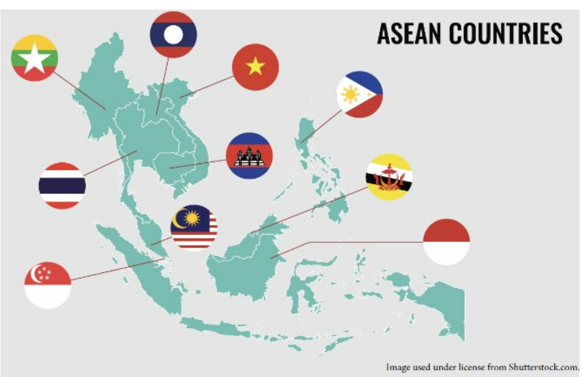

Figure 1. Map and flag representations of the AMS.

PROJECT STATUS/RESULTS: The AIMS III work is divided into three phases as follows:

Phase 1, Capacity Expansion Planning, has been completed. Under this phase, the technical potentials of VRE were identified and mapped out for the AMS. Proposals for firm generation additions and cross-border interconnections were made under different load and renewable energy scenarios. These resource scenarios were then assessed using production cost analysis to evaluate transmission flows and excess energy curtailment potentials.

Phase 2, Grid Performance Analysis, has also been completed. Current findings indicate that the interconnections proposed under Phase 1 are feasible; however, several AMS, such as Laos, Myanmar, and Cambodia will require grid strengthening for high VRE scenarios in 2030 and beyond.

Phase 3, Multilateral Market Analysis, is forthcoming and will seek to identify the barriers and challenges for VRE integration in cross-border and multilateral electricity trading.

HNEI Grid***START*** provided training to the ASEAN Center for Energy (ACE), an intergovernmental organization within the ASEAN structure representing the AMS interests in the energy sector, on production cost analysis and use of the PLEXOS software tool to empower ACE personnel to more effectively carry out project management duties for the AIMS III study.

Figure 2. Overview of ASEAN power grid.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

I7: Chulalongkorn University Smart Campus Project - ARGEMS

OBJECTIVE AND SIGNIFICANCE: In partnership with Chulalongkorn University in Bangkok, Thailand, HNEI's Grid***START*** team is field deploying multiple devices of its Advanced Real-time Grid Energy Monitor System (ARGEMS), a patented custom power meter and controller. The objective of this project is to build joint research and development capacity in the area of grid modernization and smart grid initiatives, ultimately helping to enhance energy resilience and reliability while enabling a clean energy transition.

Figure 1. Chulalongkorn University in Bangkok, Thailand.

BACKGROUND: This project is one of the collaborative activities under a Memorandum of Understanding (MOU) executed with Chulalongkorn University, Faculty of Engineering, Smart Grid Research Unit. The MOU establishes a framework for multi-year collaboration on a range of activities exploring approaches, methodologies, tools, techniques, systems, and policies around smart grid technologies on Chulalongkorn University's Smart Campus Project.

PROJECT STATUS/RESULTS: To date, two ARGEMS devices have been shipped to Chulalongkorn University. The first device has been operating in a lab setting for over a year, and the second device is ready for installation on a campus building transformer. Other devices have been prepared for final configuration and shipment.

As preparation for the deployment at Chulalongkorn University, the ARGEMS documentation was improved, and software to enable remote firmware updates, configuration, and testing for supporting a new type of current transducer (Rogowski coil) was developed.

Numerous utility use cases are under discussion and/or active development. Beyond the core sensing and distribution grid visibility, benefits of using ARGEMS devices include:

1. In-situ distribution service transformer health assessment: By estimating the health and remaining life of distribution service transformers while in field operation, predictive maintenance and associated cost reduction benefits for asset owners may be delivered. Literature review and initial hardware and software prototyping were completed to measure and utilize transformer surface temperature and vibration in conjunction with power flow. Three related articles were accepted for publication. Further research and development of this application is pending resolution of challenges with obtaining long-term transformer degradation data or performing accelerated life testing.
2. Online, distributed PV hosting capacity analysis: By using local voltage and power measurements along with stochastic power flow analysis, it is possible to streamline the determination of how much PV generation can be connected on a circuit, or even enable proactive methods to increase hosting capacity. A power flow solver and associated analysis has been demonstrated on an ARGEMS device.
3. Fault location identification: By improving the process of locating distribution faults, utilities can more quickly address issues and thus reduce repair costs and improve resiliency. A novel technique which leverages the attenuation of fault-induced grid harmonics over line distance is being explored.

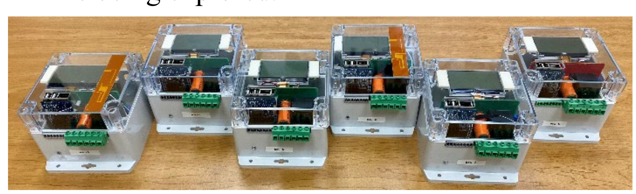

Figure 2. ARGEMS patented custom power meter and controller devices.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

Hawaiʻi Natural Energy Institute Research Highlights

Appendix I: International

I8: Technical Interconnection Requirements for Solar and Wind Projects in Laos

<u>**Objective and Significance**</u>: Under the Asia Pacific Regional Energy System Assessment (APRESA) award from the Office of Naval Research, HNEI has developed technical interconnection and performance requirements and grid codes for solar and wind projects grid interconnection in Laos.

<u>**Background**</u>: Prior to this activity, HNEI's Grid***START*** team, in partnership with USAID Clean Power Asia (CPA), had drafted interconnection grid codes for Laos' first solar pilot auction. Since these interconnection grid codes were intended for ground-mounted PV systems of no more than 10 MW per the pilot auction's allowable capacity, Électricité du Laos (EDL) requested that the support be extended to interconnection grid codes for both utility-scale and distributed PV (DPV) and wind projects.

The technical grid code requirements have a direct impact on the counter-party risk allocation in a power purchase agreement (PPA), and thus affect the commercial and financial terms of the PPA. As such, the application of technical requirements that largely utilize the inherent capabilities of current wind and solar power conversion technologies to their fullest extent must be appropriately balanced with the "bankability" concerns of financing parties. Applying its experience in commercial PPA negotiations, comprehensive knowledge of industry best practices and prior technical support to various organizations on grid interconnection codes and standards for inverter-based resources, the Grid***START*** team was well-positioned to assist EDL in this foundational effort to facilitate Laos' energy transition initiatives.

Figure 1. Rooftop solar PV array in Luang Prabang, Laos.

<u>**Project Status/Results**</u>: HNEI and USAID CPA met with EDL officials in March 2020 to launch the activity and secure necessary data and insights on EDL's grid operations.

Figure 2. HNEI Grid***START*** personnel and EDL officials at a meeting on March 12, 2020, at EDL Headquarters in Vientiane, Laos.

Following project launch, HNEI commenced work on the development of two key deliverables: (1) *Électricité du Laos Distributed Solar Photovoltaic Generating Facility Interconnection Standards* (Dec 2020); and (2) *Électricité du Laos Inverter-based Generating Facility Transmission Interconnection Standards* (Jan 2021). These deliverables were submitted and presented jointly by HNEI and USAID CPA to EDL and the Lao Ministry of Energy and Mines (MEM) in March 2021.

Figure 3: Project deliverables submitted to EDL and Lao MEM.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

Hawai‘i Natural Energy Institute Research Highlights

Appendix I: International

I9: Provincial Electricity Authority of Thailand (PEA) Collaboration

OBJECTIVE AND SIGNIFICANCE: With funding from the U.S. Office of Naval Research (ONR) under the Asia-Pacific Regional Energy Systems Assessment (APRESA) grant, HNEI's Grid System Technologies Advanced Research Team (Grid***START***) developed a capacity building program focused on renewable energy integration and smart grid technologies development and application for engineers from the Provincial Electricity Authority (PEA) of Thailand, the Thai distribution grid operator responsible for electricity supply to the entirety of Thailand, except for the Bangkok metropolis and two adjoining provinces.

BACKGROUND: Initiated in Spring 2020, the internship program was designed to accept two classes of six PEA engineers annually, participating in an eight-week curriculum of combined lectures (40 hours) and team oriented deep emersion in custom "mini-project" research, development, and test endeavors tailored to the learning needs of working utility engineers. A renewable energy integration and smart grid technologies series of lectures with emphasis on energy distribution system applications was developed and delivered to the PEA engineers. The first PEA class of interns was received at HNEI from March to May 2020. However, due to COVID-19 travel restrictions, the second intern class was postponed and bifurcated into: (1) a five-day online lecture component conducted remotely in May 2021; and (2) an in-person lecture component from October to December 2021, which is currently being conducted at HNEI.

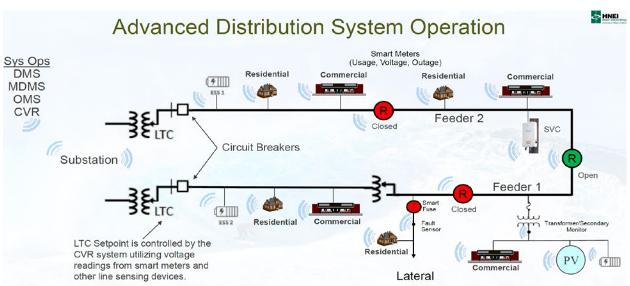

Figure 1. Sample of the teaching materials.

The training leverages the planned installation of several HNEI-developed distributed power monitoring/control units (Advanced Real-Time Grid Energy Monitoring System, or "ARGEMS") on select service transformers in PEA's service territory. The training includes mini-projects developing new sensing and controls applications residing on field-deployed ARGEMS units and bidirectional electric vehicle (EV) chargers installed by HNEI on the UH Mānoa campus.

PROJECT STATUS/RESULTS: The online component for the PEA internship in 2021 provided six PEA engineers with technical learning on topics, such as distributed energy resources (DER) technologies and microgrids. For the in-person component, the class was split into two groups, each focused on one of two mini-project topics: (1) ARGEMS application development: Distribution Secondary Fault Detection and Location; and (2) Bidirectional EV Charging Control Optimization.

In the ARGEMS mini-project, the PEA engineers engage in research to develop a sensor to detect and locate faults on primary radial distribution feeders. Specifically, this project aims to: (a) develop a fault detection and location algorithm for distribution systems using low voltage secondary service lines sensing; (b) test, calibrate, and validate the fault detection and location algorithm using available field data, lab tests, and/or simulations; and (c) integrate the developed algorithm into ARGEMS.

Figure 2. HNEI Grid***START*** patented ARGEMS devices.

In the EV Charging mini-project, the PEA engineers engage in research to develop new algorithms to optimize the charge/discharge of shared electric fleet vehicles. The objectives of this mini-project include: (a) determination of the most appropriate objective functions, constraints, and optimization solvers to expand and generalize the charge/discharge management to address larger pools of heterogeneous EVs; (b) implementation and integration of the selected algorithm into the EVs' charging control systems; and (c) testing, calibration, and validation of optimization problems using available field data, lab tests, and/or simulations.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

Hawai‘i Natural Energy Institute Research Highlights

Appendix I: International

I10: Development of BESS Technical Standards for Thailand

OBJECTIVE AND SIGNIFICANCE: The objective of this project was to provide technical assistance to support Thailand's Office of Energy Regulatory Commission (OERC) in its ultimate adoption of codes and regulations for battery energy storage system (BESS) applications in Thailand. Under contract to Abt Associates Inc., lead implementer for the USAID Clean Power Asia (CPA) program, and leveraging funding from the Asia-Pacific Regional Energy Systems Assessment (APRESA) grant funded by the U.S. Office of Naval Research HNEI's Grid System Technologies Advanced Research Team (Grid***START***) provided expert advice to OERC and Thai stakeholders, culminating in the delivery of a comprehensive guide and roadmap for developing BESS technical codes and standards for Thai regulatory action.

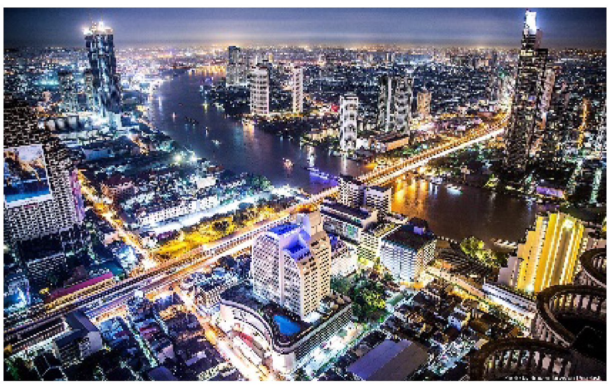

Figure 1. Bangkok, Thailand.

BACKGROUND: Propelled by the rapidly falling price for BESS around the globe, there are increasing applications of BESS by end-users, including utilities, industries, commercial businesses, 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 OERC expressed its interest to USAID CPA to develop regulations that address the engineering, performance, and safety of the installation and operation of BESS, as well as relevant electrical grid connection codes. Toward that end, Abt Associates subcontracted HNEI to develop and deliver BESS Technical Standards and provide recommendations on electrical grid connection codes to support OERC's mission to establish a regulatory foundation for the safe and reliable integration of BESS into the Thai power system.

PROJECT STATUS/RESULTS: Throughout 2020 and continuing through the first quarter of 2021, HNEI's Grid***START*** team offered technical support to the Thai OERC via its (i) review of existing BESS-relevant regulations in Thailand; (ii) offerings of expert input in stakeholder engagements, advisory group consultations and technical report review; (iii) assessment of international industry best practices, standards and codes related to BESS regulations and relevant electrical grid connection codes; and (iv) delivery of a roadmap for development of BESS codes and standards that incorporated a comprehensive topical index to current global industry best practices and citations to relevant provisions found in the leading sources of international BESS-related codes and standards. The report serves as a practical and actionable "tool" to guide regulators and stakeholders in their development of BESS-enabling standards and codes for Thailand.

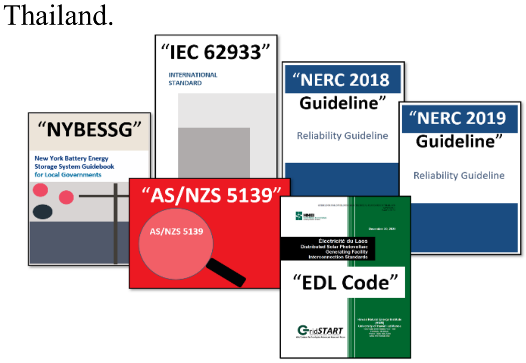

Figure 2. Selected samples of reviewed standards and codes.

Following a series of stakeholder and focus group engagements in 2020 on BESS application issues of interest in Thailand, a Final Stakeholder Consultation Workshop was held in Bangkok on February 18, 2021. Grid***START*** presented the final draft of the BESS technical standards report to OERC, with Thai electric utilities and numerous energy sector stakeholders in attendance. Stakeholder feedback was incorporated into the final deliverable "*Guidelines for Developing BESS Technical Standards in Thailand*", which was submitted to USAID CPA on March 29, 2021, for delivery to OERC.

Funding Source: Office of Naval Research

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Last Updated: November 2021

I11: Thailand Regional Solar PV Forecasting

OBJECTIVE AND SIGNIFICANCE: With funding from the U.S. Office of Naval Research (ONR) through the Asia-Pacific Regional Energy Systems Assessment (APRESA) grant, HNEI is collaborating with Chulalongkorn University and leveraging critical stakeholder feedback provided by the Thai grid operator, the Electricity Generating Authority of Thailand (EGAT), to develop a regional solar PV forecasting system for Thailand.

BACKGROUND: Investment in solar generation has increased significantly in Thailand with a decline in natural gas production and as reliance on imported fuel has increased. Thailand has high solar potential through the central portion of the country and the Thai government has supported the solar sector with feed-in-tariff subsidies. Thailand is projected to increase its solar capacity dramatically in the coming years, with significant penetration of new distributed solar systems. This project is one of the collaborative activities under the Memorandum of Understanding (MOU) executed with Chulalongkorn University, Faculty of Engineering, Smart Grid Research Unit. 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. As part of Thailand's plans to significantly increase the amount of solar energy on its power grid, EGAT recognizes the need to develop solar forecasting capabilities.

PROJECT STATUS/RESULTS: The HNEI solar forecasting system combines information derived from numerical weather prediction (NWP), satellite images, and ground based instruments to monitor current regional irradiance conditions in near real-time and predict upcoming irradiance conditions and resulting PV power production, from minutes to days ahead. HNEI's Grid***START*** team setup a new test domain for the solar forecasting system to evaluate its application in Thailand. The test domain covers northern Thailand and surrounding areas.

Day-ahead NWP forecasts are provided by the Weather Research and Forecasting system (WRF). WRF is a next-generation mesoscale numerical weather prediction system developed by the National Center for Atmospheric Research (NCAR). WRF is setup in a nested configuration, with an outer 6 km grid and inner 2 km grid focusing on Bangkok.

Hour-ahead satellite-based forecasts are derived from the Himawari-8 geostationary weather satellite operated by the Japan Meteorological Agency (JMA). Himawari-8 is considered a 4th generation geostationary weather satellite, nominally producing a new set of images every 10 minutes at 0.5 km resolution (a sample irradiance nowcast from Himawari-8 is shown in Figure 1). HNEI has access to both archived and real-time Himawari-8 images through Japan's National Institute of Information and Communications Technology.

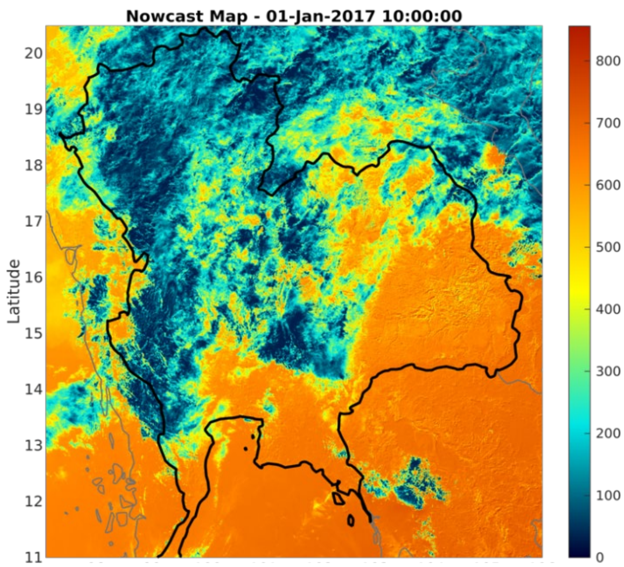

Figure 1. Sample irradiance nowcast map derived from Himawari-8 imagery.

Utilizing archived Himawari-8 images, HNEI generated a month of 6-hour ahead irradiance forecasts for over 30 test sites in Thailand. To visualize the results, a regional aggregate dashbord was developed. These results are shown using web-based visualization tools, which can be found at: http://128.171.156.27:5100/sitesforecast/.

Funding Source: Office of Naval Research

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Last Updated: November 2021

I12: USAID Papua New Guinea Electrification Partnership (PEP) Activity

OBJECTIVE AND SIGNIFICANCE: HNEI is providing technical assistance under subcontract to the Research Triangle Institute (RTI International or RTI), the prime contractor implementing the United States Agency for International Development (USAID) Papua New Guinea (PNG) Electrification Partnership (PEP) program, that aims to support PNG's enhanced electric connectivity and its goal of connecting 70% of its population to electricity by 2030. Through the expansion of reliable and affordable electricity, the partnership will help advance inclusive growth, development, and empowerment in communities throughout the country.

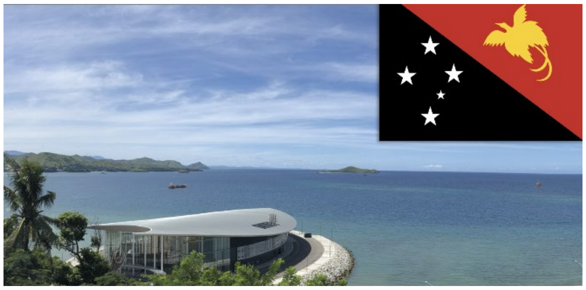
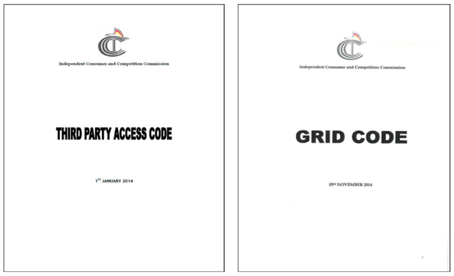


Figure 1. Ela Beach, Port Moresby, PNG.

BACKGROUND: In November 2020, the U.S. government launched the five-year, $57 million USAID-PEP program to support PNG in increasing reliable electric connectivity to its people. HNEI is contributing to this partnership by supporting RTI to: (i) improve the financial viability and operational efficiency of the country's electricity provider, PNG Power Limited (PPL); (ii) develop viable off-grid electrification models; and (iii) improve PNG's energy regulations. In particular, HNEI is supporting RTI on end-to-end utility transformation of PPL by improving competitive procurement via focus group discussions with selected government and private sector representatives and supporting the conduct of due diligence on the existing independent power producer pipeline. HNEI is supporting RTI in its effort to develop viable off-grid electrification models, including developing and executing a private sector engagement strategy for off-grid companies, building a portfolio of viable sites for off-grid electrification, and participating in stakeholder groups already working on off-grid regulations in PNG. Finally, for the demonstration of measurable improvement in PNG's energy regulator, HNEI's Grid***START*** team is assisting RTI with improving the national regulatory framework for off-grid electrification and a process for stakeholder engagement to inform and implement enabling policies and regulation.

Figure 2. Rural villages in PNG.

PROJECT STATUS/RESULTS: HNEI Grid***START***'s support of USAID-PEP to date has spanned a range of tasks, including: (1) reviewing, commenting on, and editing the draft PNG Off-Grid Regulation and underlying Off-Grid Guidelines; (2) reviewing and commenting on the appropriateness for PNG's National Institute of Standards and Industrial Technology (NISIT) to adopt certain IEC standards regarding renewable energy and hybrid systems for rural electrification; and (3) participating in numerous online meetings and workshops with stakeholders including RTI, USAID-PEP, the PNG National Energy Authority, NISIT, and the National Association of Regulatory Utility Commissioners. Currently, HNEI is reviewing the PNG Independent Consumer and Competition Commission's (ICCC) existing Third-Party Access (TPA) Code and Grid Code.



Independent Consumer and Competition Commission

THIRD PARTY ACCESS CODE

Independent Consumer and Competition Commission

GRID CODE

Figure 3. PNG TPA Code and Grid Code under review.

HNEI is tasked to provide recommended updates, comments, and edits to the codes based on industry best practices applied in the PNG context for regulatory adoption.

Funding Source: USAID-PEP

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021

Hawai'i Natural Energy Institute Research Highlights

Appendix I: International

I13: USAID Scaling Up Renewable Energy II (SURE II)

<u>OBJECTIVE AND SIGNIFICANCE</u>: Hawai'i Natural Energy Institute (HNEI) is providing technical assistance to the United States Agency for International Development (USAID) as a subcontractor under the Scaling Up Renewable Energy (SURE) II project. The project's objective is to assist partner countries in increasing the level of renewable energy and new technology into their electricity mixes, using a cost-effective, reliable, and environmentally-friendly methodology that enables countries to achieve greater self-reliance. Its expected outcomes include: increased renewable energy capacity, improved grid integration of renewable energy, increased competition for generation capacity, and dissemination of green procurement practices in project partner countries worldwide.

<u>BACKGROUND</u>: Between 2017 and 2020, the USAID SURE program helped 28 partner countries meet bold international climate commitments by accelerating their transition to more widely accessible, affordable, reliable, and sustainable energy that spurs economic growth and reduces emissions. In 2020, USAID launched the SURE II project, a five-year, $29.7 million continuation of the SURE project that prepares partners to transform their energy sectors and reap financial, social, and environmental benefits. SURE II provides support under the following six task areas:

1. Strategic Energy Planning;
2. Competitive Procurement of Renewable Energy;
3. Grid Integration of Renewable Energy;
4. End of Life Management for Advanced Energy Technologies;
5. Renewable Energy Technology and Innovation Fund; and
6. Knowledge Management and Coordination with other USAID Projects and Initiatives.

Under the leadership of the prime contractor, Tetra Tech, Inc., HNEI's Grid Systems Advanced Research Team (Grid***START)*** will engage in tasks 1, 2, and 3 to support partner countries seeking assistance under SURE II. HNEI will leverage its experience with effectively planning, procuring, and integrating renewable energy resources into power systems to provide among other services capacity-building training to partner countries. In particular, HNEI will deliver the following for the supported tasks:

- <u>Task 1</u>: Provide training via webinars on strategic planning methods and approaches and resiliency assessments.
- <u>Task 2</u>: Support developing an action toolkit, a library of best practices and model auction documents and related training, and the design of pilot auctions for renewable energy resources.
- <u>Task 3</u>: Provide training via a grid integration webinar series on topics such as forecasting, storage, curtailment, ancillary services, grid modernization/digitization, advanced unit commitment and economic dispatch, flexibility, grid integration policies, and distributed solar integration.

Each task also includes the development of "2 pager" reports on best practices within the topics of resilience assessment, auction platforms, grid impact studies, renewable energy zones, flexibility assessment, variable renewable energy (VRE) forecasting, and roadmaps for grid modernization/digitization.

Figure 1. SURE program partner countries. (Cited from <u>SURE 2020 Annual Report</u>).

<u>PROJECT STATUS/RESULTS</u>: The SURE II project is in its work plan development stage and is working with USAID to identify its initial partner countries of focus and the areas where support is needed. HNEI is ready to deliver technical support in work plan execution.

Funding Source: USAID SURE II

Contact: Leon Roose, <u>lroose@hawaii.edu</u>

Last Updated: November 2021

I14: Recommendations on Methodology for Vietnam Power Development Plan (PDP)

OBJECTIVE AND SIGNIFICANCE: As the Vietnam economy surges ahead driving dramatic year-over-year increases in energy demand, the United States Agency for International Development (USAID) Vietnam Low Emission Energy Program (V-LEEP) aims to help the Government of Vietnam (GVN) establish an effective policy, regulatory, and incentive environment for low-emission growth in the energy sector, while simultaneously attracting public- and private-sector investment in renewable energy development and energy efficiency measures.

Under the Asia Pacific Regional Energy System Assessment (APRESA) award from the Office of Naval Research, HNEI is collaborating with Deloitte Consulting, the USAID V-LEEP prime contractor, to deliver technical assistance to the GVN to address their energy growth issues.

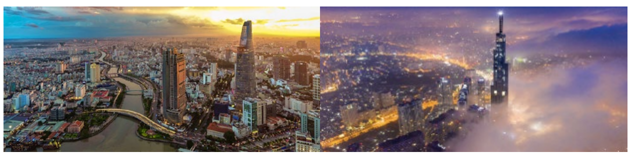


Figure 1. Day and night views of Ho Chi Minh City, Vietnam.

BACKGROUND: V-LEEP has, among other key initiatives, supported Vietnam's Ministry of Industry and Trade, Electricity and Renewable Energy Authority (MOIT/EREA) to develop Vietnam's eighth Power Development Plan (PDP-8), which is expected to incorporate advanced energy solutions, and more diversified sources of renewable energy at higher grid penetration to deliver cleaner energy future. Vietnam's PDP-8 will be the cornerstone ministerial-level plan that shapes the future of Vietnam's expanding power sector.

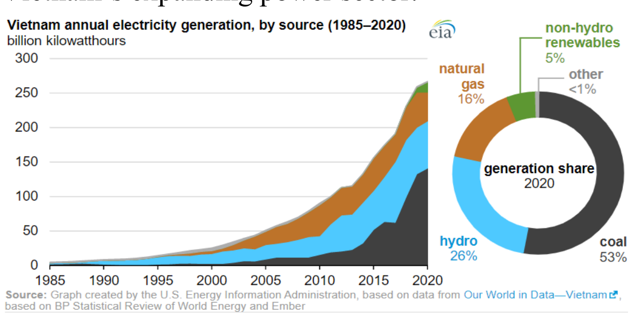


Figure 2. Vietnam's rapid growth in electricity production and resource mix.

HNEI contributed to V-LEEP's report to MOIT/EREA on a new methodology roadmap to update the historical PDP process and to incorporate international best practices for planning for higher levels of variable renewable energy. Based on the results of this assessment, MOIT/EREA has adopted V-LEEP's recommendations on a new process and methods, including the use of advanced grid simulation tools for PDP-8 analyses, including specific steps and a roadmap for implementation.

PROJECT STATUS/RESULTS: MOIT/EREA established a Modeling Working Group (MWG) to conduct production cost analysis for the development of PDP-8. HNEI's Grid***START*** team, together with V-LEEP and the U.S. National Renewable Energy Laboratory (NREL), conducted two technical trainings for the MWG and other relevant stakeholders in 2019.

The first training, *Introduction to Production Cost Modeling for Power Development Planning*, was held on November 19-21, 2019 and geared towards the Technical and Core Modeling Sub-Group of the MWG. The objective was to help participants better understand how production cost modeling can be used to analyze the operational costs and feasibility of future PDP scenarios, particularly those with higher levels of variable renewable energy. Participants were enabled to construct a model of Vietnam's grid using PLEXOS, an advanced energy market simulation software. The second training, held on December 18-19, 2020, introduced a System Advisor Model. Topics covered included flexible technologies, operating reserves, model calibration and validation, and least regrets planning.

In March 2021, with significant analytical and writing contributions by HNEI and NREL, Deloitte delivered to MOIT/EREA a technical report, *Impact Analysis of Integrating Significant Renewable Energy in Vietnam's Power Sector: A PLEXOS-based Analysis of Long-Term Power Development Planning*. The issues identified in the analyses employing advanced modeling tools can be used as feedback for generation and transmission planners to optimize the PDP-8 using the least-regret approach.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2021