UNIVERSITY of HAWAIʻI
Ke Kulanui o Hawaiʻi

David Lassner
President

DEPT. COMM. NO. 141

December 15, 2023

The Honorable Ronald D. Kouchi,
President and Members of the Senate
Thirty-Second State Legislature
Honolulu, Hawaiʻi 96813

The Honorable Scott Saiki, Speaker
and Members of the House of Representatives
Thirty-Second State Legislature
Honolulu, Hawaiʻi 96813

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

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

In accordance with Section 93-16, Hawaiʻi Revised Statutes, this report may be viewed electronically at: https://www.hawaii.edu/offices/government-relations/2024-legislative-reports/.

Should you have any questions about this report, please do not hesitate to contact Stephanie Kim at (808) 956-4250, or via e-mail at scskim@hawaii.edu.

Sincerely,

David Lassner
President

Enclosure

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UNIVERSITY OF HAWAIʻI SYSTEM
ANNUAL REPORT

REPORT TO THE 2024 LEGISLATURE

Annual Report from the
Hawaiʻi Natural Energy Institute

HRS 304A-1891

December 2023

Hawaiʻi Natural Energy Institute

School of Ocean and Earth Science and Technology

University of Hawaiʻi at Mānoa

Annual Report to the 2024 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).

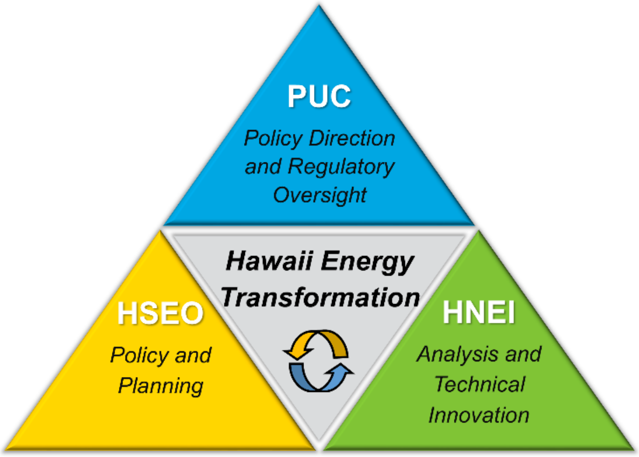
1. INTRODUCTION

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 2000s, 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). In 2022, \$0.03 (3 cents) per barrel of the ESDSF allocation was redirected to the Hawai‘i Public Utilities Commission (PUC) to support the development of EV infrastructure.

Hawai‘i’s energy transformation has been driven by bold state policies that now include a mandate for 100% renewable electricity and carbon neutrality by 2045 (HRS Secs. 269-92 & 225P-5). A core part of HNEI’s mission, going beyond traditional academic research, is to support Hawai‘i in its clean energy transformation by helping facilitate cost effective and practical solutions to deliver renewable energy for the state and its citizens. As part of this effort, HNEI robustly supports analysis to inform energy policy and decision making in Hawai‘i. The analysis conducted by HNEI and its contractors is used by the utility and PUC in their decision making. HNEI also serves as a critical bridge to 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, its partners, and its contractors. 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 significantly impact energy transformation initiatives in Hawai‘i. HNEI coordinates closely with the State Energy Office (formerly with the State Energy Coordinator), the Hawai‘i Public Utilities Commission (PUC), the state’s investor owned utility (Hawaiian Electric Company, HECO), and commercial and industrial entities. HNEI has also successfully garnered extramural funding from a range of federal sources to maximize the value of state funds to meet needs and opportunities within the state. HNEI maintains 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 with a variety of stakeholders, HNEI is able to tackle urgent and complex clean energy needs of our State, the nation, and partners in the Pacific region.



State Institutional Support

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

2. HAWAI‘I NATURAL ENERGY INSTITUTE STAFFING/FUNDING OVERVIEW

As an Organized Research Unit in the School of Ocean and Earth Science and Technology at the University of Hawai‘i at Mānoa (UH), HNEI receives state funding via the Hawai‘i General Fund through the university budget, sufficient to support its Director (Richard Rocheleau), three administrative support staff, and partial salaries (60% to 80%) of five tenure or tenure-track faculty (permanent faculty). HNEI has recently received approval to hire to additional tenure track faculty expected to help support the state’s decarbonization goals. HNEI staffing for 2023 is summarized in the Table 1 below.

Table 1. HNEI total staffing by position type for 2023.

STAFFING	Director: Richard E. Rocheleau	
	Permanent Faculty (FTE)	6
	Other Permanent Staff (APT)	3
	Temporary Faculty	13
	Other Temporary Staff [(a)] (APT, RCUH)	14
	Training [(b)]	20
	(a) Includes post-doctoral fellows	*(b) Includes graduate and undergraduate students, and visiting scientists*

As summarized in Table 2, HNEI’s primary source of funding is from extramural awards from various federal agencies. In recent years, the majority of these funds have been from the Office of Naval Research, the U.S. Department of Energy, and Naval Facilities Engineering Command, but HNEI also receives funds from other U.S. Federal agencies and industry as well. A complete breakdown of HNEI awards for FY 2021 through FY 2023 is shown in the Tables 3 through 5.

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.

HNEI also receives a small amount of tuition return. HNEI’s extramural awards also generate indirect “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.

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. Funding from the ESDSF serves as an invaluable source of funding for HNEI. The primary uses of the ESDSF over the last three years were to: 1) provide cost share to federally funded energy research when non-federal cost share is required to secure the funds; 2) provide funds to address explicit PUC and legislative requests, including unfunded legislative mandates; and 3) to support select community engagement efforts, such as the annual Hawaiʻi Energy Conference and the Hawaiʻi Energy Policy Forum, whose activities include the annual legislative energy briefing. Of the $2,308,000 encumbered or committed during FY21 to FY23, these three activities received $1,001,000, $514,000, and $293,000 respectively. The largest commitment, federal awards requiring cost share, leveraged many millions more in federal dollars that otherwise would not have been procured for Hawaiʻi use. An example is a pending, recently approved U.S. Department of Energy award awaiting final signature at the UH Office of Research Services, in which $250,000 from the ESDSF allowed HNEI to secure an additional $1 million of federal funds for advanced training in microgrid relevant areas.

During FY21 to FY23, the remaining $500,000 ESDSF funds supported general management of the ESDSF and was a major contributor to HNEI's grid studies that supported the utilities, IGP process, reliability studies associated with the retirement of the coal plant, a required assessment of Hawaiʻi's progress toward its Renewable Portfolio Standard goals and many other analysis of future grid operations that have been presented to HECO and to the PUC. These activities are generally cost shared via funding HNEI receives from the Office of Naval Research. Leveraging the ESDSF in this way, amplifies the benefits for Hawaiʻi residents.

Generally, HNEI does not initiate legislation but, as evidenced by the project summaries in Appendices A and 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. A breakdown of HNEI funding by type for the past three fiscal years is shown in the Table 2 on the following page, including the ongoing leveraging of the ESDSF.

Table 2. Funding by source and year, FY 2021 to FY 2023.*

	FY 2021	**FY 2022**	**FY 2023**
General Funds	$1,296,118	$1,329,727	$1,259,349
Tuition and Fees S Funds	$25,173	$49,897	$32,870
Extramural Awards	$15,123,364	$15,205,393	$13,932,226**
Research and Training Revolving	$433,925	$351,258	$445,870
Energy Systems Development Special Fund	$507,000	$914,000	$887,000
**ESDSF shows funds in year funds are committed or encumbered. All others shown in year funds are awarded.*	***Includes $8,388,656 approved by federal agencies but awaiting final approval by UH Office of Research Services.*		

Table 3. Summary of HNEI Extramural Funding, FY 2021.

Office of Naval Research, Asia-Pacific Energy Systems	$4,070,000
Office of Naval Research, Sustainable Energy Systems	$5,530,000
NAVFAC, Wave Energy Test Site	$3,137,889
U.S. Dept. of Defense, Sustainable Aviation Fuels	$136,765
FAA, Sustainable Aviation Fuels	$200,000
U.S. Dept. of Energy, Island Energy Resilience	$125,000
U.S. Dept. of Energy, Grid Technology via Washington State University	$31,063
U.S. Dept. of Energy, Wave Energy Conversion Development	$253,727
U.S. Dept. of Energy, Marine Center Infrastructure	$999,997
City and County of Honolulu, Energy Efficiency	$119,000
SINTEF (Norway), Biocarbons	$35,189
Trevi Systems, Battery Testing	$50,000
Dept. of Defence (Australia), Battery Testing	$204,033
Element Energy, Battery Testing	$170,669
USAID, International via Tetra Tech	$60,032
FY 2021 Total	**$15,123,364**

Table 4. Summary of HNEI Extramural Funding, FY 2022.

Office of Naval Research, Sustainable Energy Systems	$6,249,889
NAVFAC, Wave Energy Test Site	$6,000,000
FAA, Sustainable Aviation Fuels	$100,000
U.S. Dept. of Energy, Hydrogen Storage	$710,304
U.S. Dept. of Defense, Sustainable Aviation Fuels	$88,201
U.S. Dept. of Energy, Island Energy Resilience	$105,000
U.S. Dept. of Energy, Wave Energy Conversion Development via OSU	$63,898
U.S. Dept. of Energy, Grid Technology via UAF	$190,732
U.S. Dept. of Energy, Grid Technology via WSU	$6,564
State of Hawai‘i - DAGS, Wave Energy Conversion Development	$199,978
USAID, International via RTI International	$92,039
USAID, International via Tetra Tech	$10,869
Delphos International, Grid Analysis	$34,952
RTI International, Grid Analysis	$310,233
Accure Battery Intelligence (Germany), Battery Testing	$239,941
SINTEF (Norway), Biocarbons	$2,793
National Science Foundation, Materials Research	$800,000
FY 2022 Total	**$15,205,393**

Table 5. Summary of HNEI Extramural Funding, FY 2023.

Office of Naval Research, Fuel Cells	$200,000
NAVFAC, Wave Energy Test Site	$3,637,609
FAA, Sustainable Aviation Fuels	$400,000
U.S. Dept. of Energy, Island Energy Resilience	$105,000
U.S. Dept. of Energy, Thin Films and Printable PV	$450,000
U.S. Dept. of Energy, Grid Technology via UAF	$154,988
USAID, International via RTI International	$257,485
Deloitte & Touche, International	$238,579
Nuvera Fuel Cells, Fuel Cells	$99,999
FY 2023 TOTAL	**$5,543,660**

Pending UH ORS Approval

Office of Naval Research, Sustainable Energy Systems	$4,600,000
U.S. Dept. of Energy, Durable Hydrocarbon FC Membranes	$1,800,000
U.S. Dept. of Energy, MicroGrid Training	$1,000,000
U.S. Dept. of Energy, Encapsulation of Perovskite Fuel Cells	$375,000
U.S. Dept. of Energy, Power Systems, Dynamic Converter Systems	$136,079
U.S. Dept. of Energy, 2D Materials for Solar Films	$250,000
Sintef, Biocarbons	$27,399
Element Energy, Battery Testing	$200,178
Total Pending UH Signature	**$8,388,656**

FY23 plus awards pending UH signature	**$13,932,316**

3. RESEARCH SUMMARIES

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

In 2023, within these areas, HNEI conducted or provided leadership for 58 discrete projects. Of these 58 projects, approximately 35% are funded or co-funded by the ESDSF. 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" summaries 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 (https://www.hnei.hawaii.edu/). Updates to projects are available on our website during the year. Sources of funding for each of the projects are also identified within the summaries.

Brief summaries of what is included in each of the nine Appendices and a full listing of their corresponding page numbers follows.

Appendix A: Hawaiʻi Energy Analysis – Community Support

HNEI and its contractors conduct analysis across a broad range of issues. These are a result from legislation or more informal requests based on discussions with legislators or state agencies, with the primary agency being the Hawaiʻi Public Utility Commission (PUC). They may also arise from interactions with the utility, but only where they address broader state or PUC interests. During this reporting period, the work has relied heavily on models and data developed by HNEI and its primary consulting partner, Telos Energy. The focus of the efforts in this section tend to be analyses related to more immediate problems facing Hawaiʻi's electricity grids and policy makers. The work described in Appendices A1 and A2 provide direct support to the Hawaiʻi Public Utilities Commission, including HNEI's recently submitted analysis of the state's utility companies' progress toward the 2030 Hawaiʻi RPS goals. Appendix A3 describes work initiated with a legislative request to evaluate the disposal and recycle of clean energy products in Hawaiʻi. Appendices A4 and A5 supported the utility's IGP analysis and the Hawaiʻi Energy Policy Forum, respectively. HNEI's work with various energy communities are summarized in Appendices A6 and A7. Finally, Appendix A8 describes HNEI support of the Hawaiʻi State Energy Office (HSEO), including support of the state's Powering Past Coal Taskforce.

Appendix B: Hawaiʻi Energy Analysis – Grid Reliability

As part of its work to support the state's progress to achieve very high penetration of renewable energy, HNEI and its contractors conducted a series of studies to assess the reliability of the islands' grids as distributed rooftop solar and the pending utility scale solar + storage projects are deployed. A series of studies involving Oʻahu and Maui are presented in Appendices B1 through B4.

Appendix C: Future Energy Systems

While conducting modelling in support of the state's progress to achieve very high penetration of renewable energy, HNEI and its contractors identified a number of longer term issues and opportunities that are expected to have potentially significant impact on the reliability and operations of Hawaiʻi's electric grids. HNEI analysis has shown that the utilities can achieve very high penetration of renewables using variable energy sources paired with the current 4-hour battery technology. However, these studies also provided clear evidence that, at the highest penetration levels, some form of "firm" generation would be needed to provide grid services. In Appendix C1, we identify the capacity of firm generation required for different levels of solar/wind/storage penetration. Appendices C2 through C3 assess the potential for hydrogen or long duration storage to meet these needs. Appendix C4 evaluates the impact of load shifting to reduce firm power needs. Appendix C5 summarizes work to better understand the ventilation required to maintain safe indoor work environments.

Appendix D: Grid Technology Development

With its very high penetration of distributed rooftop solar and the pending utility scale solar + storage projects, Hawaiʻi 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 Hawaiʻi'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 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 Hawaiʻi leveraged with funding from the ESDSF.

Appendices D1 through D7 summarize seven microgrid relevant technology development efforts. These include: development and demonstration of a high efficiency DC microgrid at Coconut Island; development of advanced conservation voltage reduction technology demonstrated at the Marine Corps Base on Okinawa; continued development and demonstration of a virtual power plant on Maui, a project focused on understanding the dynamic response of inverter dominated power systems; development and deployment of a bidirectional EV charging system on the UH campus for optimized ride sharing; planning for EV charging infrastructure for USMC Camp Fuji in Japan; and continued development of an advanced power systems laboratory.

Appendix E: Alternative Fuels

Alternative fuels have always been an important component of Hawaiʻi's efforts to reduce its dependence on imported petroleum and an essential component for reducing Hawaiʻi's greenhouse gas footprint. While early projects focused primarily on power and ground transportation applications, sustainable aviation fuels are garnering increased interest in Hawaiʻi and nationally. Within this topical area, HNEI conducts research, testing, and evaluation that seeks to support the potential for alternative fuels production in Hawaiʻi. HNEI projects include two projects focused on sustainable aviation fuels (Appendices E1 and E2), and one focused on enhanced fuels characterization methodologies (Appendix E3). HNEI is also actively researching the production of novel biocarbon materials using a slow pyrolysis process (Appendix E4), novel processes for production of solar fuels with primary emphasis on photoelectrochemical hydrogen production (Appendix E5), and Appendix E6 provides an update to HNEI's efforts to provide technical support and fuel (hydrogen) for several electric-fuel cell hybrid buses to be operated by the Hawaiʻi Island Mass Transit Agency (Hele-on bus).

Appendix F: Electrochemical Power Systems

HNEI has been conducting research, development, and testing of fuel cell and battery technologies for over two decades. 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. Appendix F summarizes the ten distinct projects HNEI conducts in this area. Appendix F1 summarizes HNEI's ongoing partnership with the Naval Research Laboratory to develop reliable fuel cell power systems for unmanned aerial vehicles. Appendices F2 through F7 describe multiple approaches for development of more efficient, lower-cost fuel cells, including both proton-exchange and anion-exchange membrane technologies. Appendices F8 through F10 describe three projects focused intended to inform the use of Li-ion energy storage systems. More detailed descriptions of each of these efforts are found in Appendix F.

Appendix G: Advanced Materials

The seven projects included in the Advanced Materials group, include three projects focused on the development of novel techniques for the production of thin-film materials for electronic and solar application low cost photovoltaics (Appendices G1 through G3); one project focused on the development of low cost, high performance hydrogen storage technologies (Appendix G4); an ongoing effort to develop novel solutions for forward osmosis seawater desalination (Appendix G5); and a description of a research and education collaboration with the University of Washington, funded by the National Science Foundation (Appendix G6), and an fundamental research project to design and develop advanced air filtration materials for energy applications (Appendix G7).

Appendix H: Ocean Energy

Since 2015, HNEI has been engaged in a cooperative effort between the U.S. Navy and U.S. Department of Energy to support testing of pre-commercial wave energy conversion devices in a real-world operational setting offshore from Marine Corps Base Hawai‘i. 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 (ONR) titled “Asia-Pacific Regional Energy Systems Assessment (APRESA),” intended to facilitate development of clean, resilient, and efficient energy systems throughout the Asia-Pacific region. HNEI has leveraged this initial ONR funded effort to develop a wide range of partnership and new funding sources derived from USAID and World Bank programs. Appendix I1 provides an overview of the APRESA award and very brief summaries of a number of projects under this award, including ones in Vietnam, Thailand, Indonesia, Cambodia, and the Philippines. Appendices I2 and I3 provide additional detail for two of the many projects initiated under APRESA. Appendices I4 through I7 summarizes the recent work supported by USAID and the World Bank (via subcontracts to the prime) that took place across the Asia-Pacific region, including in Papua New Guinea, the Philippines, and Indonesia. Appendices I8 and I9 summarize other island specific studies in the Asia-Pacific region and Caribbean, respectively.

APPENDICES

Appendix F: Electrochemical Power Systems

Appendix G: Advanced Materials

Appendix H: Ocean Energy

Appendix I: International

A1: Decision Support Services to the Hawaiʻi Public Utility Commission

OBJECTIVE AND SIGNIFICANCE: HNEI provides regular technical analysis and assistance to the Hawaiʻi Public Utilities Commission (PUC). This support provides ongoing review of utility plans and technical challenges faced by the electricity grid during the transition to higher renewable energy. By providing an unbiased, technical review of utility plans and grid challenges, HNEI has established itself as a trusted third-party in ongoing dockets and policy discussions.

BACKGROUND: The 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.

Examples of past support included a review of HECO's distributed energy resources (DER) Grid Service definitions [Docket #2019-0323], the economic merits of HECO's standalone battery proposals [Docket #2020-0136], and benefits and challenges of biomass conversion for the AES coal plant [Docket #2021-0024].

This paper briefly discusses four recent examples of HNEI support to the PUC. These are also described in more detail in other project summaries located in this report.

- AES retirement and replacement;
- Maui oil unit retirement and replacement;
- Firm renewable needs; and
- Time of use rates and equity.

PROJECT STATUS/RESULTS: The HNEI-Telos team met with the Commission in person in January 2023 to discuss ongoing developments at the utility, HNEI analysis, and other critical issues for the state.

AES Retirement and Replacement (Appendix B1): The AES Hawaiʻi coal plant, the largest power plant on Oʻahu retired on September 1, 2022. This retirement decreased the amount of dispatchable fossil capacity available to the utility by more than 10%. Throughout 2021 and 2022, the HNEI-Telos Energy team routinely conducted reliability analysis of the retirement to brief HECO, the PUC, and the Governor's Power Past Coal Task Force on the impacts of project delays, cancellations, and other events [Docket #2021-0024]. 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 work are expected to have important implications for power system planning and policy for Oʻahu.

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, and new trends in HECO's generator outage rates (-), the recent failure of Kahe 4 (-), project delays (-), and load (+). Analysis shows that with the retirement of AES in September with only one replacement resource available (Mililani I, 39 MW). In 2023, an additional resource was brought online (Waiawa I, 36 MW), but challenges in commissioning and testing the KES standalone battery have continued to challenge Oʻahu reliability. Fortunately peak levels on Oʻahu continue to trend well below pre-pandemic levels. Oʻahu, however, is currently in a supply deficit until the KES plant is brought online or other Stage 1 and 2 solar + storage resources become available.

Maui Oil Unit Retirement and Replacement (Appendix B2): The Kahului Power Plant (KPP) is scheduled to retire by the end of 2024. Analysis in 2021 showed how the retirement could be reliably achieved with proposed solar + storage projects. Since that analysis, project delays have occurred with replacement resources. In addition, the Māʻalaea M10-M13 diesel engine may need to be retired earlier than expected. The combined retirements would represent the loss of over 85 MW of firm capacity, over 40% of Maui's peak demand.

Similar to the work conducted in Oʻahu, the objective of this study was to update the 2021 analysis and reevaluate Maui's reliability if one or both of the plants are retired and evaluate potential mitigations necessary. The results of this analysis were briefed to the PUC [Docket #2021-0024] and the Maui Accelerating Clean Energy & Decarbonization Technical Working Group (ACET) and are expected to have important implications for power system planning and policy for Maui.

The HNEI-Telos team continues to monitor ongoing developments in Maui, including the status of Stage 1 and Stage 2 project commissioning, adoption of DER and BTM storage, peak load levels, and generator reliability. While the M10-13 plants are expected to remain available for 4-5 more years, any new capacity additions beyond those under development in Stage 1 and 2 will likely take that much time or longer. As a result, HNEI will continue to support the Commission with independent reviews of Maui reliability.

Clean Firm Needs (Appendix C1): HNEI conducted a study to inform ongoing procurement and proposed legislation for both variable and firm renewable energy. It sought to determine the minimum amount of firm power that the system would require at various levels of wind, solar, and storage additions. It also informed decisions on whether to integrate more variable renewable energy today, considering that these decisions may shut the door on future options. This information can be used to determine characteristics of future systems to inform decisions on oil-fired power plant retirements, procurement of new resources, and to show how robust the system can be with variable renewable energy and storage alone.

In 2023, HNEI expanded that analysis to consider specific resources that could provide the firm renewable needs, including biodiesel, hydrogen, and multi-day energy storage. As specific projects are considered in the Stage 3 Firm Renewable RFP [Docket #2017-0352] – the results of which are expected by the end of 2023, HNEI will review proposals and provide recommendations and analysis to the Commission upon request.

Time of Use Rates and Equity (Appendix C4): In 2023, there were two notable developments at the Commission. The first was the acceptance of HECO's proposed time of use (TOU) rates [Docket #2019-0323] and a new docket and priority afforded to customer equity [Docket #2022-0250]. To support the Commission in their review of these priorities, the HNEI-Telos team conducted a TOU Rate analysis.

This work included a review of HECO's AMI data to calculate changes to bill payments with and without the new TOU structure. This analysis quantified bill impacts ($ and %) across a sample of several thousand HECO ratepayers using actual, 15-minute interval consumption data. This analysis also allowed the study to calculate changes in revenue for the utility and the potential for costs to shift from TOU early adopters to other ratepayers and current solar customers. This raises concerns over equity because some lower income ratepayers may not be able to adopt new technologies to benefit from load shifting and TOU rates.

As the regulatory priorities in Hawaiʻi continue to shift, HNEI will support ongoing analysis and recommendations to ensure a fair, cost-effective, renewable energy transition for the state. In 2024, HNEI anticipates supporting a review of the Stage 3 RFPs, ongoing reliability concerns, and further support for land use and equity concerns.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2023

A2: Evaluation of the State Renewable Portfolio Standards Mandate

OBJECTIVE AND SIGNIFICANCE: The State of Hawai‘i's ("State") energy policy is driven, in significant part, by the State's Renewable Portfolio Standards (RPS) that mandate the percentage of electricity that must be generated from renewable energy resources at different times until achieving 100% in 2045. The RPS targets have evolved through several legislative amendments since the RPS was first established in 2001. The current RPS, under § 269-92, Hawai‘i Revised Statutes (HRS), was modified by ACT 140 of the 2022 legislature requiring electric utilities in the State to report electricity from renewable sources based on a percentage of electricity generation including distributed generation.

HNEI is required by legislation to provide regular technical analysis and assistance to the Hawai‘i Public Utilities Commission (PUC). As part of this assistance, HNEI provides the PUC with an update of the status of the RPS every five years. This year's analysis report is the fourth that HNEI has performed since 2008. HNEI's analysis is used by the PUC in the development of their report to the legislature.

BACKGROUND: Hawai‘i's RPS is intended to promote Hawai‘i's energy policy goals by encouraging the development and implementation of locally-sourced renewable energy generation connected to Hawai‘i's utility electricity systems, resulting in the displacement of existing fossil fuel generation and reducing the State's dependence on imported oil. The PUC is required by statute to evaluate Hawai‘i's RPS every five years and report its findings to the Legislature. The objective is to determine if the standards established by HRS § 269-92 remain effective and achievable based on progress to date and to analyze options for meeting RPS targets in the future. Hawai‘i's initial RPS was established in 2001 (Act 272, Session Laws of Hawai‘i 2001). The most recent modification to the RPS occurred in July 2022. Act 240 (HB 2089) was signed into law that amended the RPS calculation from renewable energy as a percentage of sales to renewable energy as a percentage of total system generation. The new calculation is based on total generation (including generation from private rooftop solar, in the denominator) and total renewable generation (including generation from private rooftop solar, in the numerator). The current RPS goals, by year, are summarized in Table 1.

Table 1. Hawai‘i's Renewable Portfolio Standards by year.

Compliance Year	RPS Requirement (% of Generation)
2010	10%
2015	15%
2020	30%
2030	40%
2040	70%
2045	100%

PROJECT STATUS/RESULTS: The RPS is applied separately to Kaua‘i Island Utility Cooperative (KIUC) and Hawaiian Electric Company (HECO). In performing the analysis necessary for this Report, the HNEI relied on several sources of information including:

- *Annual Utility RPS Status Reports*: Each of Hawai‘i's electric utilities provides annual reports identifying the amount of energy generated by renewable sources and the achievement of the RPS requirements. These reports identify renewable generation resources that are operating as of the dates of the reporting periods. The Commission relies on these reports to quantify historical and existing renewable energy generation. The most recent reports by each utility indicate RPS achievement information for the calendar year 2022.
- *Future Renewable Generation Projects*: This includes new renewable generation projects that provide electrical power to each utility. Expected renewable generation for these projects is provided by the utilities, based on current estimates. The Commission relies in this Report on approved applications to quantify expected renewable energy generation from projects that are under construction or substantially in progress. In addition, for the HECO Companies, the ongoing competitive-bid process for new renewable generation includes information regarding the possible scope of new renewable resources in the near- to-mid-term. For HECO, more than 500 MW of renewable projects are expected to come online in the next few years.
- *Mid- and Long-Range Utility Planning Estimates*: Hawai‘i's electric utilities also

provide the Commission with mid-term and long-range planning information and projections of expected and possible capital expenditures in filed reports, periodic briefings, and the Integrated Grid Planning (IGP) process. Planning information includes identification of possible specific future renewable generation projects, possible requests for proposals, and general estimates of possible resource potential.

- *Additional Expert Opinion*: External expert opinion was also factored into the analysis and commentary. A number of anonymized state-based experts were interviewed to obtain their views on the future achievement of RPS goals. These experts including those from non-governmental organizations (NGOs), independent power producers, the utilities, academia, and state agencies.

Key findings in HNEI's 2023 Report include:

- Achievement of the 2030 RPS requirement of 40% is likely for HECO service territory, which includes O‘ahu, Maui County, Hawai‘i Island, and is essentially certain for KIUC. As of 2022, KIUC has already achieved the 2030 goal.
- Based on current plans for the PUC approved Stage 1 and Stage 2 PV plus storage projects, the HECO territory is expected to reach the 40% by 2030. However, force majeure and related supply chain issues have created problems for State 1 and Stage 2 projects. If these issues continue, it could create problems in achieving the 40% mandated goal. Additionally, the recent Lahaina wildfires could potentially impact the pace of new renewable energy generation on Maui.
- The RPS has led to a substantial reduction of Greenhouse Gases (GHGs) being emitted in the electricity sector. However, GHGs have not diminished significantly in other sectors (transportation, buildings, etc.) as much as the Hawai‘i Clean Energy Initiative (HCEI) originally projected.
- Increasing electric loads from electric vehicle adoption will make it more difficult to achieve the RPS targets in the future, but will ultimately benefit statewide emissions.
- The costs of renewable energy projects under development and recently proposed in Hawai‘i remain at or below costs of oil-fired generation, making renewable projects cost-competitive alternatives compared to continuing to utilize fossil fuel generation resources. However, recent events including delays in the development of HECO Stage 1 and 2 projects have led to increased costs for renewable energy development and deployment.
- Initial analysis by HNEI to explore the ability to integrate solar plus storage or solar/wind and storage suggests that reaching the 70% RPS target by 2040 is feasible and likely cost effective with current technologies. However, land use, community engagement, and transmission will need to be carefully managed.
- The RPS remains effective in helping the State achieve its policies and objectives with respect to developing renewable energy resources in Hawai‘i.

However, it should be noted that in 2022, while customer-based generation was the largest single source of renewable energy at the end of the year, the advances in the development of utility-scale renewable generation have been significant since the 2018 assessment. Figure 1 is a pie chart showing the relative percentages of resources providing electricity from renewables statewide.

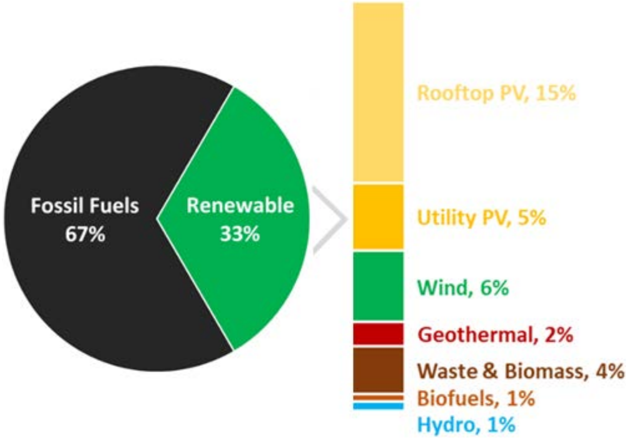


Figure 1. Percentages of renewable resources and technologies providing electricity for Hawai‘i.

Figure 2 shows progress against the RPS by Island. The Report provides additional detail for the KIUC and HECO service areas. The downturn evident for 2022 is due to the new method required for estimation of the renewable fraction which is now based on total generation, not just utility sales.

While the outlook for meeting the 2030 goals is excellent, the Report notes a number of concerns about meeting the future RPS mandated goals (70% in 2040 and 100% in 2045). This concern is due to a variety of factors. These include issues concerning reliability and resiliency, land availability (particularly on Oʻahu), local community acceptance, transmission interconnections, the demand increased electrification of transportation and buildings will place on the RPS, and uncertainties regarding the emergence of newer technologies and resources to meet the expected need for dispatchable firm power to maintain reliability. A more complete discussion can be found in **HNEI's Report to the PUC**.

Funding Source: Energy Systems Development Special Fund

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2023

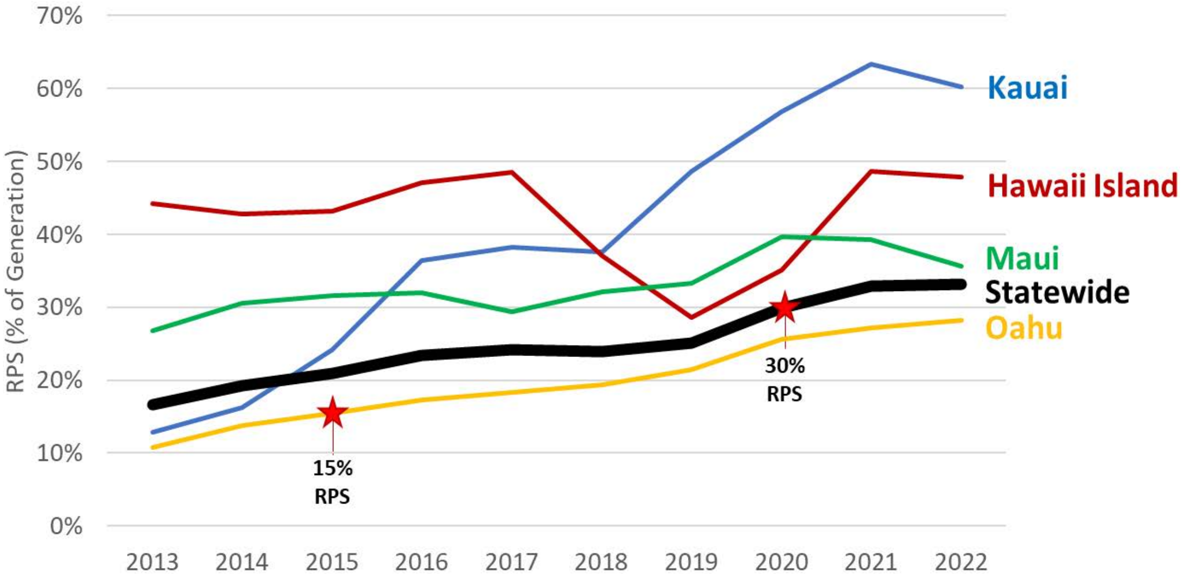


Figure 2. Consolidated progress in meeting RPS goals by Island.

Hawaiʻi Natural Energy Institute Research Highlights

Appendix A: Hawaiʻi Energy Analysis – Community Support

A3: Disposal and Recycling of Clean Energy Products in Hawaiʻi

OBJECTIVE AND SIGNIFICANCE: Hawaiʻi's pursuit to become fully renewable by 2045 will produce substantial streams of clean energy waste over the next 30 years and beyond. In recent years, Hawaiʻi has seen large 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. Due to this, it is crucial for the state to manage these waste streams in a manner that is both safe and environmentally sound. The objective of this work is twofold: 1) to quantify this waste stream and best practices for their cost-effective recycle and 2) to conduct a comprehensive technical assessment to determine best practices for disposal, recycling, or secondary use of clean energy products produced in the State.

BACKGROUND: The 2021 Hawaiʻi State Legislature passed House Bill 1333 which required that the Hawaiʻi Natural Energy Institute, in consultation with the Hawaiʻi State Department of Health, conduct a thorough study on best practices for disposal and recycling of discarded clean energy products in Hawaiʻi. Specific deliverables addressed were: 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 2021, remains ongoing. Findings to date include: 1) identifying material composition of PV panels, inverters, cabling, and mounting equipment as a function of installed power (kg/kW); 2) quantifying the cumulative PV installed by island for residential, commercial, and utility scale since 2005; 3) calculating the projected loading rate of aging PV materials as far out as 2045; 4) determining the preliminary estimates of installed battery capacity at residential, commercial, and utility scale; 5) evaluating estimates of material composition of PV battery as a function of installed power (kg/kW); 6) conducting a comprehensive assessment of waste treatment options, costs, and risks; and 7) conducting a comprehensive assessment of fee options and recommendations. Specifically:

1. As of 2021, it is estimated that 3.86 million modules have been installed on Oʻahu, 720,000 in Maui County, 580,000 in Hawaiʻi County, and 480,000 on Kauaʻi. A total of 225,000 tons of PV related clean energy materials have been installed in Hawaiʻi through 2021. For context, the total amount of municipal solid waste and commercial/demolition waste generated in the State during 2021 was 2,570,478 tons. The total amount of these PV related clean energy materials installed to date totals 8.8% of all municipal solid waste and commercial/demolition waste generated across the entire State in 2021.
2. The cost of disposing PV panels and Li-ion batteries will require one or more revenue-generating schemes to be established; potentially including waste generator responsibility, extended producer responsibility, state assisted recycle, and state encouraged recycle. The recommendation is to establish a process that covers the full price of their off-island disposal.
3. The possibility of enhanced restrictions or banning of ocean shipping of end-of-life Li-ion batteries was identified as an existential threat to Hawaiʻi's disposal of these products.
4. To address this threat, the need to deactivate Li-ion batteries or even fully recycle Li-ion batteries on island was identified in order to ensure long term access to ocean transport.

These and other results have been detailed in HNEI's report "***Recommendations on Waste Management of Clean Energy Products in Hawaiʻi***," which was previously submitted to the legislature. Although not mandated, this work was continued in 2022 to add depth to policy recommendations for the disposal and recycling of clean energy materials in Hawaiʻi and a **supplemental report** was produced and is available on HNEI's website.

Funding Source: Energy Systems Development Special Fund

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Last Updated: November 2023

A4: 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 and continued to stay engaged in the TAP throughout 2022 and 2023.

KEY RESULTS: HNEI's involvement in the IGP and its previous leadership role in the TAP 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 to identify "bookends" to delineate the potential impacts of load uncertainty. During 2021, significant effort was expended by HNEI to quantify alternative probabilistic methodologies and metrics other than energy reserve margins (ERM), with the potential for enhanced insights, in determining resource adequacy. These probabilistic tools were 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 #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,

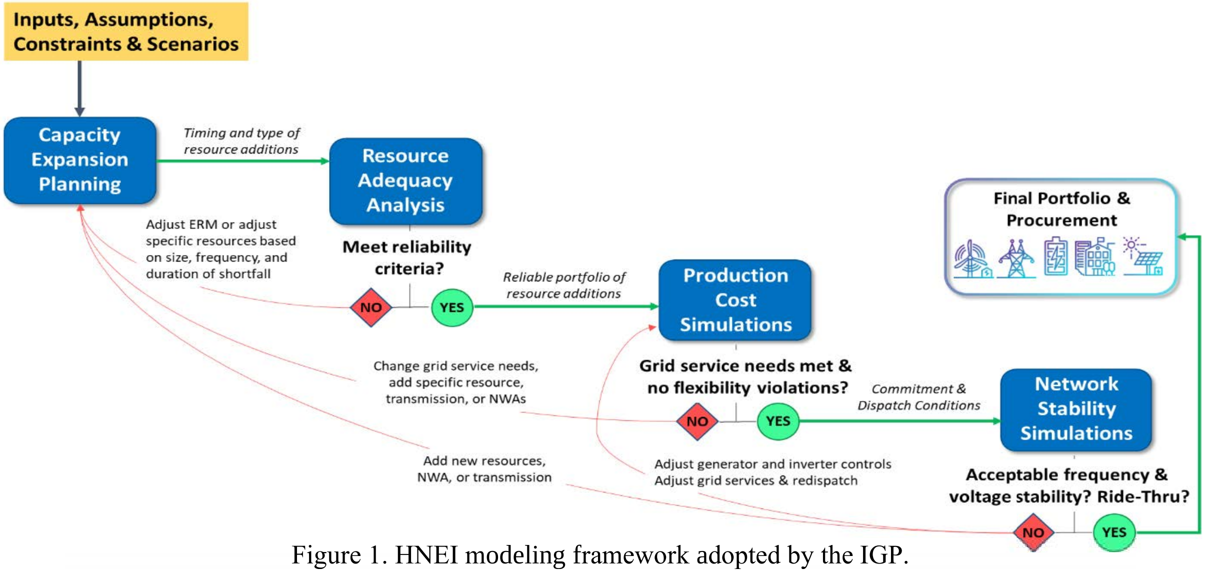

Figure 1. HNEI modeling framework adopted by the IGP.

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 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 ended in early 2022. Despite no longer chairing TAP, HNEI and their contractor Telos Energy continue to be actively engaged as a member in the TAP as well as other parts of the IGP stakeholder process, including active involvement in the Stakeholder Committee, the Stakeholder Technical Working Group, and relevant TAP subgroups.

In 2022, HNEI and its contractor, Telos Energy, raised numerous concerns and corrective recommendations 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.

As a result of these recommendations, HECO adopted HNEI's probabilistic analysis framework at the end of 2022 and throughout 2023. Now included in all of the IGP filings as well as HECO's RFP is a probabilistic framework that quantifies the loss of load probability across different future resource mix years and procurement cycles. It considers the impact of forced outages, load variability, and weather impacts on solar and wind resources.

Throughout 2023, HNEI and Telos Energy actively engaged in the TAP's Transmission sub-committee, and the Resource Adequacy sub-committee. Considerable attention was paid to the Energy Reserve Margin, HECO's novel approach to resolving challenges associated with the planning reserve margin (PRM) commonly used across the power industry. Based on written feedback and recommendations the Commission ordered HECO to conduct a third-party led study to evaluate different options for PRM and ERM methodologies in Hawaiʻi. In 2023, HECO engaged with their consultant (E3) and conducted the ordered study. Throughout this process, HNEI and Telos Energy provided numerous recommendations, written comments, and several discussions with the HECO and E3 team to provide recommendations.

The IGP culminated in 2023 and ended a multi-year process to lay out HECO's long-term plan to reaching 100% renewable energy by 2045 as well as intermediate goals. The final IGP was filed with the Commission on May 12, 2023 and HNEI and the TAP filed 111 public comments during the review process. The IGP is currently under review by the Commission.

In parallel to the Commission review, HECO is continuing its competitive solicitation process via the Stage 3 RFP. HNEI and Telos Energy have provided both the Commission and HECO feedback on this

RFP and are awaiting notification of the selected projects. At that time, the HNEI-Telos team will review proposed projects and may conduct independent reviews of modeling and analysis if requested.

As the IGP continues into its next phase, 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; Office of Naval Research

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix A: Hawaiʻi Energy Analysis – Community Support

A5: Hawaiʻi Energy Policy Forum

OBJECTIVE AND SIGNIFICANCE: Through this project, HNEI supports and manages the Hawaiʻi Energy Policy Forum (HEPF) in its mission to advance Hawaiʻi's energy transition through energy stakeholder engagement in fact finding, analysis, information sharing, and advocacy that enables informed decisions.

BACKGROUND: The HEPF was established in 2002 by the University of Hawaiʻi's College of Social Sciences (CSS) Public Policies Center (PPC) as a collaborative energy planning and policy group consisting of Hawaiʻi's electric utilities, oil and synthetic 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 commissioned studies, reports, and briefings to raise the level of dialog concerning energy issues for legislators and the general public.

The Forum has, in past years, sponsored and organized Legislative Briefings 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. Among its members, HEPF has more than 75 representatives from the electric utilities, oil and natural gas suppliers, environmental and community groups, renewable energy industry, academia, and federal, state and local government all working together to seek smart energy solutions to sustain a healthy prosperous, and secure Hawaiʻi.

The Forum's mission is to share ideas and information, recommend and advocate policies and initiatives, and promote civic action to achieve a clean and sustainable energy future for Hawaiʻi. To this end, it conducts research, briefings, forums for informative and deliberative dialogue and policy development, annual legislative briefings, and outreach and public education. HEPF also produces the biweekly "Hawaiʻi: State of Clean Energy" production, streamed on ThinkTech Hawaiʻi (https://thinktechhawaii.com/), and made available on the HEPF website.

PROJECT STATUS/RESULTS: In 2021, the CSS PPC was eliminated by the University of Hawaiʻi and management of the HEPF program was assumed by HNEI. HEPF held the 2022 Legislative Briefing on Friday, January 28th. The theme of the Legislative Briefing was focused on gaps in Hawaiʻi's energy infrastructure and how the $1.2 billion Infrastructure Investment and Jobs Act signed by President Biden on November 15, 2021 could be used to address the most vulnerable aspects of that infrastructure.

In 2022, the HEPF took the following actions:

- Creation of online informational resources for members and the public focusing on compilation of the significant new federal policies related to energy which includes a description of the policy, policy type, relevant sector, funding opportunities, and managing agency. Initially, this featured the Infrastructure Investment and Jobs Act, and later included the Inflation Reduction Act; and
- Formation of Committees on Port Resilience, Geothermal Energy, and Recycling of Clean Energy Materials to explore how investments in renewable microgrids, firm renewable energy, and PV and battery energy storage system recycling could improve island community resilience and Hawaiʻi's economy.

HEPF held the 2023 Legislative Briefing ("Briefing") on January 12 at the University of Hawaiʻi at Mānoa campus. The Briefing's theme "Strategic Alliances for Decarbonization and Energy Self Sufficiency". focused on gaps in Hawaiʻi's energy infrastructure and how the Infrastructure Investment and Jobs Act and the Inflation Reduction Act could be used to address the most vulnerable aspects of that infrastructure. This event also celebrated the HEPF's 20th anniversary.

The U.S. Deputy Secretary of Energy David Turk presented the Keynote Address – affirming the strength of our historic partnership with the Department of Energy and introducing a panel discussion with the newly inaugurated Governor of Hawaiʻi, Josh Green. This was followed by a full day of panel discussions and briefings. The Briefing also concluded Climate Week, a collaboration organized by HEPF and the State of Hawaiʻi's Climate Change and Adaptation Commission. Following the final panel discussion, the participants proceeded to Washington Place for a 20th anniversary reception hosted by the Governor and First Lady. Video of the Briefing and its agenda can be found at https://manoa.hawaii.edu/hepf/index.php/elementor-homepage/2023-legislative-briefing/.

In response to the critical needs addressed during the Briefing, HEPF created an online informational resource for members and the public focusing on compilation of the significant new federal policies related to energy which includes a description of the policy, policy type, relevant sector, funding opportunities, and managing agency. Initially, this featured the Infrastructure Investment and Jobs Act, and later included the Inflation Reduction Act.

With the departure of a key member of HNEI's faculty who managed the HEPF activities through the 2023 legislative briefing, the HEPF is again at a decision point. The HNEI is committed to the success of the HEPF and expects to expand support staff in the near future.

HAWAIʻI NATURAL ENERGY INSTITUTE
HAWAIʻI ENERGY POLICY FORUM
UNIVERSITY OF HAWAIʻI AT MĀNOA

Funding Source: Energy Systems Development Special Fund

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Last Updated: November 2023

A6: Molokaʻi Community Energy Resilience Action Plan

OBJECTIVE AND SIGNIFICANCE: In 2022 and 2023, stakeholders in Molokaʻi developed the Community Energy Resilience Action Plan (CERAP). The CERAP is a first of its kind initiative in Hawaiʻi and represents an independent, island-wide, community-led & expert-informed collaborative planning process to increase renewable energy on Molokaʻi. HNEI supported the CERAP process by providing technical expertise, data, modeling capabilities, and technical reviews throughout the project.

KEY RESULTS: On July 7, 2023, Sustainable Molokaʻi and the Molokaʻi Clean Energy Hui submitted the first Molokaʻi Community Energy Resilience Action Plan (Molokaʻi CERAP 1.0) to the Commission (Docket #2019-0178) in collaboration with the Molokaʻi community and HNEI as the lead technical partner. This community-led, island-wide plan is a road map "to achieve 100% renewable energy for Molokaʻi that is feasible, respectful of Molokaʻi's culture and environment, and strongly supported by the community."

BACKGROUND: For many years Molokaʻi stakeholders and community members have expressed concerns over power system reliability, affordability, equity, and engagement. A primary concern of the community is that their priorities and values were not reflected in the planning process conducted in HECO and the Commission's conventional planning studies (PSIP and IGP).

As a result, several utility-scale renewable energy projects were proposed and ultimately cancelled due to community opposition. These projects included large utility-scale wind projects and inter-island cables connecting Molokaʻi to Maui and Oʻahu, as well as smaller hybrid solar and storage projects. When HECO last initiated a competitive procurement for new renewable generation, Molokaʻi stakeholders requested that the Commission pause any procurement to allow for a community-based planning process to outline local priorities and objectives to achieving a 100% clean electricity.

Since 2020, the Sustainable Molokaʻi and the Hui conducted a stakeholder-driven, community-led planning process to solicit input on key priorities and objectives. HNEI was selected to augment this community engagement with technical analysis.

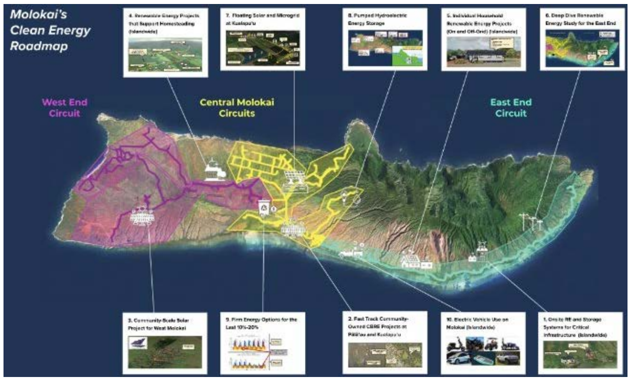

Figure 1. Molokaʻi Clean Energy Roadmap.

PROJECT STATUS/RESULTS: Throughout the CERAP 1.0 process, HNEI advised Molokaʻi stakeholders on utility-planning processes, data collection, and preliminary grid modeling. The HNEI team developed a simplified power system dispatch tool to select candidate resource portfolios and evaluate load, renewable generation, storage scheduling, curtailment, and oil consumption. The tool was developed using Excel-based formulas and dashboards to allow easy use, dissemination, and testing among Molokaʻi stakeholders.

The HNEI team also met with Sustainable Molokaʻi on-island in January 2023 to review project status, discuss opportunities to improve the analysis, and to better understand community objectives and power system infrastructure. After this meeting, the HNEI team helped to identify potential tax credits available in the Inflation Reduction Act, and helped scope out potential future analysis necessary to continue the CERAP planning process.

The final CERAP 1.0 report was filed with the Commission in July 2023. HNEI will continue to stay engaged in both the Commission's regulatory review, HECO's standard planning processes (IGP), and the Molokaʻi Community's CERAP 2.0 analysis.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2023

A7: Energy Transition Initiative Partnership Program

OBJECTIVE AND SIGNIFICANCE: The Energy Transition Initiative Partnership Program (ETIPP) is a program with an initial three-year term established and funded 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 2020, HNEI was selected via a competitive solicitation to be the Pacific Regional Partner, one of five regional partners initially selected nationwide, to help communities coordinate with National Renewable Energy Laboratory (NREL) personnel to; solve critical questions and issues of importance by communities engaged in energy transitions, to support replicable energy transition technical assistance and knowledge sharing to inform, and to support energy transitions throughout the United States.

BACKGROUND: ETIPP provides technical assistance opportunities for remote, island, and islanded communities. Through its understanding of 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. 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: 1) prioritize community energy values, goals, challenges, and opportunities; 2) identifies and advances the ability to implement strategic, whole-systems solutions; and 3) fosters 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 2021-2022, HNEI led efforts to seek qualified applicants for technical assistance and initial onboarding and orientation training session for representatives of five awarded Pacific Region Cohort 1 and 2 projects and participated in the delivery of training and technical assistance.

In 2022, HNEI supported the successful conclusion of the two Cohort 1 projects. The first, a Cohort 1 project proposed by community partner, Hawaiian Electric Company (HECO), identified locations within its distribution service territory in Honolulu deemed most appropriate for hybrid microgrid development. Such a map – perhaps the first in the United States developed by a utility – is intended to improve resilience of remote and low-lying electricity grids in the face of severe weather conditions, which have the potential to cause long-duration power outages. An example of the hybrid microgrid map for the northeast Oʻahu community of Hauʻula is shown in Figure 1.

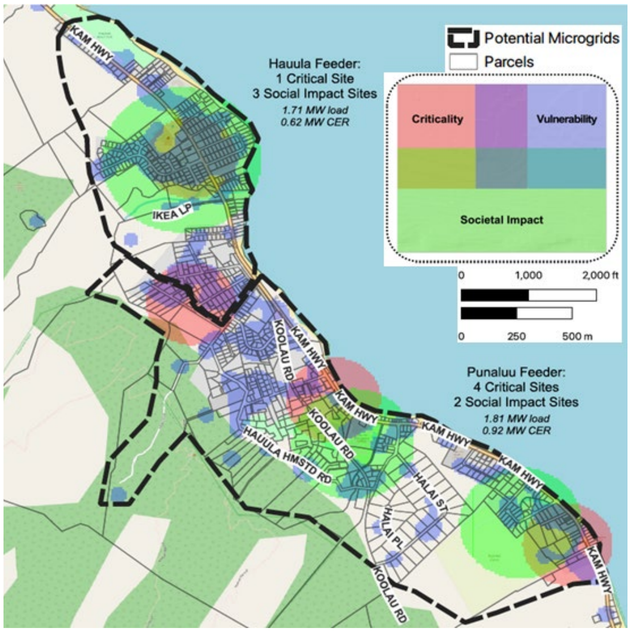

Figure 1. Potential Hauʻula sites for hybrid microgrids.

The second Cohort 1 project completed during 2022 was the County of Kauaʻi's "Electric Vehicle and Multi-Modal Transportation Transition" project, which supports the island's effort to eliminate fossil fuel use in the ground transportation sector by 2045.

The Kauaʻi program's technical assistance 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.

Results of the projects from Cohort 1 have been submitted to NREL.

In 2022, HNEI also supported the selection and scoping efforts for three projects under Cohort 2 in the Pacific Region, which are as follows.

Hui o Hau‘ula, Hawai‘i (2022-2024):
Hui o Hau‘ula, a community organization of O‘ahu, is coordinating the planning and development of a Community Resilience Hub, which will include the generation and storage of power for the surrounding Ko‘olauloa District. HNEI is collaborating with NREL on evaluating a portfolio of renewable energy technologies for the Resilience Hub. The project will develop technical guidance and documentation for storm and disaster energy resilience throughout Ko‘olauloa.

University of Hawai‘i, Hawai‘i (2022-2024):
The University of Hawai‘i’s project plans include analyzing the potential for geothermal cooling in buildings across its 10 campuses. HNEI is supporting NREL’s efforts to conduct analysis on building heating and cooling loads at select locations and support NREL’s modeling of shallow geologic conditions. The objective is to recommend geothermal technologies, materials, and design approaches that improve energy efficiency and significantly increase sustainability across campus communities. Outcomes will include increased capacity for geothermal energy analysis at the University and opportunities to apply project results in similar environments.

Guam Power Authority, Guam (2022-2024):
The Guam Power Authority (GPA) is seeking assistance on renewable energy resource integration, improved utility planning and energy security, and to establish a performance management system for its Clean Energy Master Plan.

In 2023, Mark Glick, HNEI’s PI for the execution of this work took a leave-of-absence from HNEI to become the state’s Chief Energy Officer. In order to compensate for the loss of Mr. Glick, HNEI hired Skog Rasmussen LLC to support HNEI’s community efforts. Funds from the ESDSF were committed to this effort to ensure that all program requirements were met. During 2023, HNEI’s team participated in the first Regional Partners meeting held in Denver, Colorado and worked with local communities to identify two additional applicants for Cohort 3.

Of the two Cohort 3 applicants – only one, the Moloka‘i Community Hui – was selected to move forward. The Moloka‘i application includes the three activities below, which are currently being developed for potential inclusion in the Scope of Work for Cohort 3.

1. Assessing the feasibility and cost-effectiveness of floating solar at the Kualapu‘u reservoir in central Moloka‘i, for which there is strong community interest.
2. Development of planning for renewable energy – a top community priority – for a range of critical infrastructure, county wide.
3. With a shared location at Kualapu‘u reservoir, the community is interested in the feasibility of pumped-storage to meet community needs.

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

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Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix A: Hawaiʻi Energy Analysis – Community Support

A8: Hawaiʻi State Energy Office Support

OBJECTIVE AND SIGNIFICANCE: Following extensive discussions with the Hawaiʻi State Energy Office (HSEO), HNEI and HSEO identified several potential project areas in critical need of additional resources for continued progress for Hawaiʻi's energy transition. An agreement was reached for HNEI to support the HSEO to conduct work in various areas with the objective to address critical energy transition needs.

BACKGROUND: In February 2019, the Research Corporation of the University of Hawaiʻi, on behalf the University of Hawaiʻi's HNEI entered into an agreement with the State of Hawaiʻi, Department of Business, Economic Development, and Tourism, State Energy Office to conduct work and accelerate state progress in the areas of Energy Efficiency, Renewable Energy Generation Diversification and Support, Grid Opportunity Assessment, and Clean Transportation. In July 2021, following a period of limited activity the agreement with DBEDT was modified to include the following activities:

Task 1: Renewable Energy (RE) Generation Diversification and Support to support professional and technical services, subject matter expertise, analysis, and/or support in the development and diversification of renewable energy generation toward meeting state energy policies and goals. The objective of this Task is to provide information and coordination assistance to facilitate permitting and interconnection of renewable energy projects to support project siting and reduce project conflicts and delays. This task explicitly included support for the Powering Past Coal task force in support of Act 23, Session Laws of Hawaiʻi 2020, and statewide coordination tasks assigned to the Hawaiʻi State Energy Office by Act 122, Session Laws of Hawaiʻi 2019, and in Chapters 125, 141, and 196 of the Hawaiʻi Revised Statutes.

Task 2: Grid Opportunity Assessment to support development of models for energy and decarbonization policy considerations for alternative pathways to achieve a particular end-state. HSEO proposed that a University of Hawaiʻi at Mānoa's Data Science Institute Fellow ("Fellow") will create and run modeling scenarios, generate datasets, and communicate the results with data visualizations to provide insights on the relative benefits and impacts to the electric sector of achieving state policy through different strategies, such as straight fuel switching (gasoline to electric) versus a combination of fuel switching (gasoline to electric) and transportation efficiencies.

Task 3: Clean Transportation Transition Support is intended to support professional and technical services, subject matter expertise, analysis, and/or support to promote an accelerated transition to clean ground transportation and advance state transportation energy policies and goal. The objective of this task is to automate the collection and preparation of data sets, load the data into a database accessible to both internal and external stakeholders to the extent possible, perform analyses, and develop data visualizations to address policy and technology questions relevant to Hawaiʻi's transition to a net negative carbon economy by 2045.

PROJECT STATUS/RESULTS: HSEO has reported substantial progress in each of the three tasks. Highlights of those accomplishments by task are summarized below.

Task 1 RE Generation Diversification and Support:

a) HSEO staff supported of the Powering Past Coal Task Force, conducting approximately monthly meetings and development of a Master Schedule. Separately, HNEI developed an easy to use tool to assess monthly Oʻahu grid reliability for different build-out scenarios for the Stage 1 and Stage 2 solar plus storage plants.
b) HSEO staff participated in and provided input to a coordination effort convened by the County of Maui in response to a Public Utilities Commission and Maui Electric Company letter. The Maui-focused group, the Maui County Accelerating Clean Energy and Decarbonization Implementation Technical (ACED-IT) Working Group, was intended to emulate the success of Oʻahu's Powering Past Coal Task Force. As stated in the letter, "one of the lessons from retiring the AES coal plant on Oʻahu is that cooperation with local government and community engagement improves the likelihood of success for the entire set of needed actions. Based on our successful experience with Governor Ige's Powering Past Coal Task Force on Oʻahu, we are requesting

an opportunity for similar collaboration with your Administration."

c) Important data, geospatial analysis, and general project development and permitting information have been provided to support the appropriate and effective siting of future renewable energy projects. Examples include maps used in presentations and on the HSEO website, input on land use ordinance revisions, estimates of greenhouse gas emissions, continued work on property tax issues, community outreach, and formal comments to the utility and Public Utilities Commission regarding the Stage 3 request for proposals seeking firm and renewable generation on O'ahu, Maui, and Hawai'i Island.

Task 2 Grid Opportunity Assessment:

a) The Fellow incorporated technology and resource inputs and specifications from Hawaiian Electric's IGP Inputs and Assumptions workbooks into the O'ahu and Hawai'i Island open source Engage model developed by NREL. Baseline runs to test the model's stability and ability to run scenarios that incorporate generic capacity expansion and existing generation resources have been performed.
b) The Fellow supported development of written documentation detailing the source of all inputs, constraints, technology configurations, resource profiles that are in the current working HSEO's O'ahu and Hawai'i Island Engage model.
c) The Fellow has also provided support on the Maui, Moloka'i, and Lāna'i Engage models and the development of a data pipeline that will enable the outputs from capacity expansion and decarbonization scenarios that are run within engage to be loaded into the HAVEN web application for comparative analytics and immersive visualization.

Task 3 Clean Transportation Transition Support:

a) The Fellow contributed to the development of an updated version of the HAVEN web application, immersive data visualization tool tailor made to facilitate comparative analytics of capacity expansion and production cost scenario outputs. The Fellow completed a beta version of an updated version of the HAVEN web application, an immersive data visualization tool tailor made to facilitate comparative analytics of capacity expansion and production cost scenario outputs. The decarbonization of transportation scenarios are expected to be prominent components of HSEO's Act 238 Decarbonization Pathways report.

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

Contact: Richard Rocheleau, rocheleau@hawaii.edu

Last Updated: November 2023

B1: O‘ahu Near-Term Grid Reliability with AES Retirement

OBJECTIVE AND SIGNIFICANCE: The AES Hawai‘i coal plant, the largest power plant on O‘ahu retired on September 1, 2022. This retirement decreased the amount of dispatchable fossil capacity available to the utility by more than 10% and was the largest single source of electricity on O‘ahu. From 2021 to 2023, the HNEI-Telos Energy team routinely conducted reliability analysis of the retirement to brief HECO, Hawai‘i Public Utilities Commission (PUC), and the Governor’s Power Past Coal Task Force on the impacts of project delays, cancellations, and other events. 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 amid generation shifts. 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 previously 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, and new trends in HECO’s generator outage rates (-), the recent failure of Kahe 4 (-), project delays (-), and load (+). Analysis shows that with the retirement of AES in September 2022, with only one replacement resource available (Mililani I, 39 MW) and later (Waiawa I, 36 MW) in 2023, O‘ahu is currently in a supply deficit until other Stage 1 and 2 solar + storage resources become available.

However, as of September 2023, recent trends in the O‘ahu peak load, which are still approximately 100 MW lower than pre-pandemic levels, mitigate much of the reliability risk through the end of 2023 and start of 2024.

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 occurred with the retirement of the AES coal plant in September 2022.

SB 2629 enacted in 2020 bans coal-fired generation in Hawai‘i after 2022, ensuring the AES retirement. The initial objective of this study, requested by the PUC, was 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 now that the AES coal plant is retired.

The Stage 1 and 2 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. As of October 2023, only two of the remaining seven projects are online and operating, with the remaining projects not expected until 2024. As a result, the power system is currently in a supply deficit.

Since the completion of the 2021 analysis, numerous events and trends occurred on O‘ahu that required a reevaluation of O‘ahu’s reliability:

1. Continued project delays across most of the Stage 1 and Stage 2 projects continue to be a risk to O‘ahu grid reliability. The primary AES capacity replacement (185 MW standalone KES BESS) originally delayed until May 2023, experienced a failure during commissioning and testing – pushing back the projected online date until the end of 2023 at the earliest.
2. The Kahe 4 (90 MW) oil generator was removed from service due to equipment failure in July 2022. This plant was expected to be back online

by Spring 2023, but as of October 2023, it remains offline.

3. There was a notable increase in HECO's forced outage rates during 2020 and 2021 due to both aging of existing thermal units and modification of operations during COVID.
4. While project delays have exacerbated risk to the O'ahu grid, peak load dropped noticeably during the pandemic and has not yet recovered. It remains below the forecasted level, mitigating some of the reliability risk.

Given these changes, the PUC requested a refresh of the 2021 reliability analysis to evaluate system reliability through the end of 2022 and 2023.

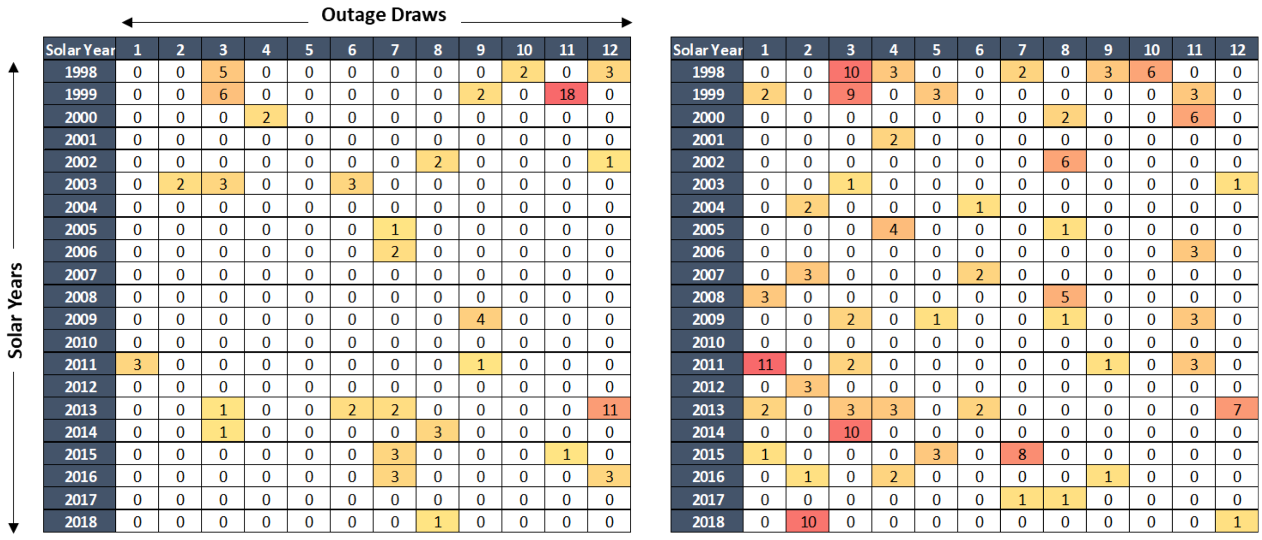
Novel stochastic modeling methodologies – developed by HNEI and Telos Energy and summarized in HNEI's 2021 report to the legislature – that accurately account for the chronological operations of storage, solar variability, and generator outages are being utilized to determine if the proposed solar + storage systems can maintain reliability in the coming year. 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. The methodology developed by HNEI and Telos Energy is now also being deployed in HECO's Integrated Grid Planning (IGP) process.

<u>PROJECT STATUS/RESULTS</u>: The stochastic methodology 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 draws 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. An example of this process is provided in Figure 1.

This methodology was repeated across 27 cases, which evaluated a range of three solar + storage levels, three peak load levels, and three forced outage rates.

1. Solar + storage of 39 MW (Mililani), 89 MW (+Waiawa & West O'ahu), and 139 MW (+Ho'Ohana)
2. Peak load values of 1085 (2022 data), 1150 (IGP), and 1215 MW (2017-2019 data)
3. Forced outage rates of 7.5 (2015-2019), 11 (midrange), and 15% (2020, 2021)

Each of these cases was evaluated with and without the Kapolei Energy Storage (KES) battery energy storage system for a total of 54 scenarios.



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

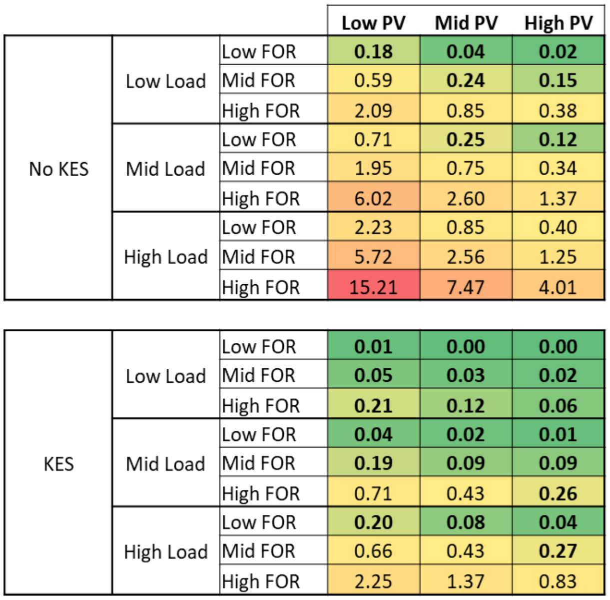
Solar Year	1	2	3	4	5	6	7	8	9	10	11	12
1998	0	0	10	3	0	0	2	0	3	6	0	0
1999	2	0	9	0	3	0	0	0	0	0	3	0
2000	0	0	0	0	0	0	0	2	0	0	6	0
2001	0	0	0	2	0	0	0	0	0	0	0	0
2002	0	0	0	0	0	0	0	6	0	0	0	0
2003	0	0	1	0	0	0	0	0	0	0	0	1
2004	0	2	0	0	0	1	0	0	0	0	0	0
2005	0	0	0	4	0	0	0	1	0	0	0	0
2006	0	0	0	0	0	0	0	0	0	0	3	0
2007	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.

Unlike the results provided in 2021, which were predicated on a single estimate of forced outage rates, system load, and replacement schedules, this analysis was reported in a manner that allowed a user to select any level of solar, forced outage, and load plus KES operability for any given month to calculate key resource adequacy metrics (LOLE, LOLH, EUE, etc.). The resulting customizable tool was provided to key stakeholders participating in the Governor's Powering Past Coal Task Force to allow for ongoing evaluation of results as new data arises and timelines of resource construction projects change.

Results of the 54 evaluated cases are provided in the matrix in Figure 2, which shows the loss of load expectation – measured in average days of capacity shortfall in a year – across a range of solar + storage replacement, load levels, forced outage rates, and with and without the KES battery. Higher numbers, highlighted in yellow and orange, represent conditions with high risk.



			Low PV	Mid PV	High PV
No KES	Low Load	Low FOR	**0.18**	**0.04**	**0.02**
		Mid FOR	0.59	**0.24**	**0.15**
		High FOR	2.09	0.85	0.38
	Mid Load	Low FOR	0.71	**0.25**	**0.12**
		Mid FOR	1.95	0.75	0.34
		High FOR	6.02	2.60	1.37
	High Load	Low FOR	2.23	0.85	0.40
		Mid FOR	5.72	2.56	1.25
		High FOR	15.21	7.47	4.01
KES	Low Load	Low FOR	**0.01**	**0.00**	**0.00**
		Mid FOR	**0.05**	**0.03**	**0.02**
		High FOR	**0.21**	**0.12**	**0.06**
	Mid Load	Low FOR	**0.04**	**0.02**	**0.01**
		Mid FOR	**0.19**	**0.09**	**0.09**
		High FOR	0.71	0.43	**0.26**
	High Load	Low FOR	**0.20**	**0.08**	**0.04**
		Mid FOR	0.66	0.43	**0.27**
		High FOR	2.25	1.37	0.83

Figure 2. LOLE (days per year) for 2023 evaluated across 54 scenarios.

In the summer of 2023, replacement resources experienced another setback when the KES (185 MW) battery energy storage system had an equipment failure during commissioning and testing. Current information about the failure is sparse and treated as confidential, but the expected commercial online date for the plant is deferred another four to five months until late December 2023.

One example of the results converted into a monthly forecast is provided in Figure 3. This was developed assuming the current schedule of replacement resources, including the cancellation of KES, and load remaining below pre-pandemic levels throughout 2023.

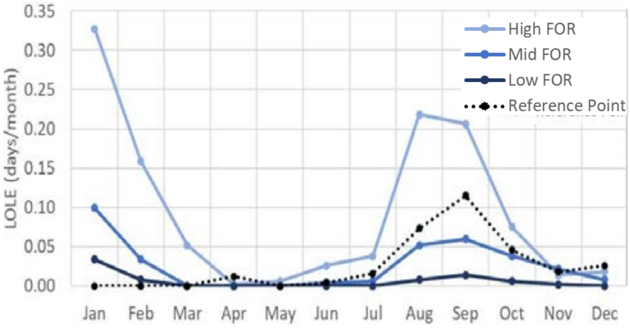


Figure 3. Expected monthly loss of load expectation based on current proposed schedules and returning load.

The KES resource is a critical component of O'ahu's reliability plans, at least until the remaining Stage 1 and Stage 2 solar and storage projects come online. If continued delays occur and load growth returns to pre-pandemic norms, then the reliability of the O'ahu system could be jeopardized. Currently load levels remain low and O'ahu is now exiting the seasonal peak demand period, suggesting that reliability risk will remain low until next Spring at which point KES is expected to be operational.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2023

B2: Maui Near-Term Reliability and Kahului Retirement Analysis

OBJECTIVE AND SIGNIFICANCE: The Kahului Power Plant (KPP) was once scheduled to retire by the end of 2024, but delays in procurement and construction of replacement resources have pushed that date back to 2027. In addition, the Māʻalaea M10-M13 diesel generators have been identified for retirement in 2027 due to lack of replacement parts. Both units will need to be retired due to emissions compliance and air permitting regulations. The objective of this study was to update the 2021 and 2022 analysis and reevaluate Maui reliability if one or both of the plants are retired and evaluate potential mitigations necessary to preserve system reliability. The results of this analysis were briefed in 2022 to the Hawaiʻi Public Utility Commission (PUC) and the Maui Accelerating Clean Energy & Decarbonization Technical Working Group (ACET) 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, was conducted. It was found that either the KPP or M10-13 retirements without deployment of other generation sources would significantly reduce system resource adequacy as measured by loss of load expectation (LOLE). However, the analysis showed that partial deployment of proposed hybrid solar + storage projects would improve system reliability compared to current reliability levels, but that additional resources beyond the 80 MW currently under construction will be necessary to meet reliability requirements if both plants are retired.

The number and size of proposed replacement projects, the retirement timeline, and the ability to extend KPP and/or M10-M13 operation, if necessary, makes the reliability risk on Maui less acute than the situation on Oʻahu, but time is running out for new replacement resources to be available in time.

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 (HECO):

> *"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."*[1]

The retirement of KPP has been planned for several years and in 2021 HNEI conducted a detailed evaluation of its replacement with the proposed Stage 1 and Stage 2 solar + storage projects. These projects included 135 MW of solar with 540 MWh of storage, along with a 40 MW, 160 MWh standalone battery in Waena. Projects were originally anticipated to come online between 2022 and 2023, but project delays and supply-chain constraints have occurred – cancelling some projects and pushing online dates back to 2024 or potentially 2025. Additional projects being proposed face growing community opposition and increased project costs. The Lahaina wildfire and reconstruction efforts may also further challenge new replacement resources.

In addition, since the reliability analysis conducted in 2021, HECO was notified replacement parts may no longer be available for the M10-M13 diesel units. According to the manufacturer, "the engines have manufactured for more than about 40 years ago, some engine-related parts might no longer be available for supply due to the business closing at our suppliers and if there is no alternative way to produce parts anymore. So in that case we will officially inform you that the parts cannot be supplied as an response to your each RFQ."[2]

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[1] HECO Kahului Power Plant Transition Plan, April 5, 2021, Docket No. 2021-0024.

[2] HECO letter to the PUC, March 21, 2022, Docket No. 2021-0024.

HECO notified the PUC that they only have parts on hand to service the units through the first half of 2024. After that date, HECO anticipated a potential end of life around 2025-2026. Given the project delays and uncertainty in the Stage 1 and 2 solar + storage projects and the uncertainty in the future of KPP and M10-13 generating units, HNEI was asked by the Commission to reevaluate grid reliability on Maui in 2022.

HECO's final Integrated Grid Planning (IGP) Inputs and Assumptions were finalized after the 2022 analysis was completed. As such, HNEI completed a reevaluation of the retirement plans with new load growth forecasts as an input into the efforts to assess load flexibility on Maui. This 2023 analysis was largely consistent with earlier analyses and identified portfolios of resources capable of replacing the aging fossil fuel generators.

Since this analysis was completed, wildfires on Maui have devastated the community and focused attention on the utility's plans for the future.

<u>PROJECT STATUS/RESULTS</u>: To assess the reliability (specifically resource adequacy) of the Maui system with the KPP and M10-13 retirement and replacement solely with variable renewable energy and energy storage, HNEI and Telos Energy conduced a resource adequacy analysis. This process was utilized by HNEI throughout 2021-2023 and recently adopted by HECO. It utilizes sequential Monte Carlo probabilistic modeling which incorporate 22 years of chronological solar data, 8 years of chronological wind data, and hundreds of samples of thermal generator outages. This is the same probabilistic methodology used to evaluate the AES coal plant retirement on O‘ahu.

Grid simulations were conducted across seven scenarios with assumptions on load, DER integration, and other system details derived from HECO's IGP assumptions for the year 2026. The Reference Point scenario assumed the current grid's resource mix, including KPP and M10-13, without additional retirements or new solar resources. Three additional scenarios were evaluated; 1) with KPP retired, 2) with M10-13 retired, and 3) with both KPP and M10-13 retired. This evaluated retirement levels between 33 MW and 82 MW.
This analysis was similar in nature to the work conducted in 2021 and 2022, but was updated in 2023 to reflect recent cancellations and delays in Stage 1 and Stage 2 replacement resources as well as recent changes to the Maui load forecast.

Each of these scenarios was evaluated without any replacement resources, and across a range of solar + storage replacements from 20 MW to 180 MW, using equal 20 MW tranches of new resources. In addition, the matrix of cases was conducted with and without the 40 MW Waena standalone battery system, which has not yet received Commission approval. A chart of the installed capacity evaluated in the Reference Scenario, the retirement scenarios, and the replacement scenarios is provided in Figure 1.

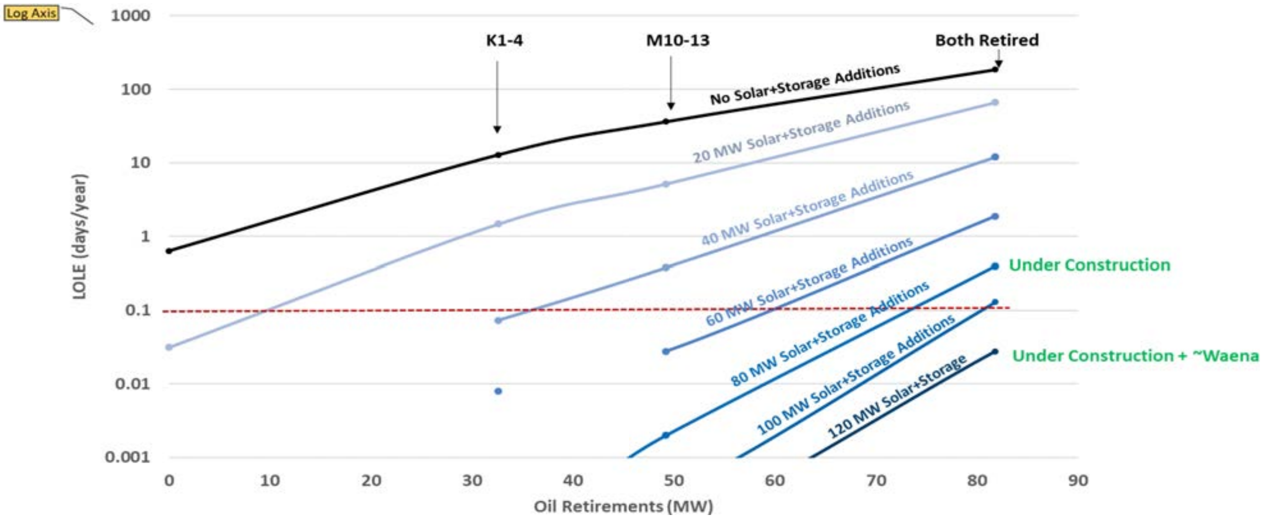

Figure 1. Loss of Load Expectation with oil retirements and solar + storage replacement.

Each case was analyzed across 506 random samples (replications) of chronological dispatch, representing 22 years of weather data (23 solar, 8 wind) and 22 outage profiles per weather year (506 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 2 with which shows the total amount of capacity retirements (MW) on the x-axis, and the loss of load expectation (LOLE, days per year) on the y-axis (note log axis). Loss of load expectation measures the number of days in the year where the Maui power system would have insufficient resources to meet demand, thus requiring emergency measures or rolling blackouts. Each dot measures the overall system reliability under a given assumption of thermal retirement (K1-4, M10-13) and solar + storage replacement. Contour lines are provided to allow interpolation across a range of retirement and replacement options.

This probabilistic approach – evaluated across a range of both retirement and replacement resource options – clearly shows the relationship between retirement and required replacement resources to allow for easy interpretation as timelines shift.
These results indicate that with the K1-4 retirement in isolation (-33.5 MW), any combination of 40 MW of solar + storage or standalone storage resources brings the system back to its current level of reliability (i.e. a near 1-1 replacement of oil with solar + storage). The retirement of M10-13 in isolation (-50 MW), would require more replacement resources, between 40 and 60 MW – again a near 1-1 replacement. With both oil plants retired (-81.8 MW), between 80 and 100 MW of replacement solar + storage capacity would be required to maintain reliability. This highlights that full deployment of the under-construction hybrid solar + storage resources plus additional resources would be required to meet current system reliability levels.

Another way to visualize the data, shown in the Figure 2, isolates the reliable scenarios for replacement. This visualization makes the gap more apparent between the resources currently under construction and the resources needed to retire both units.

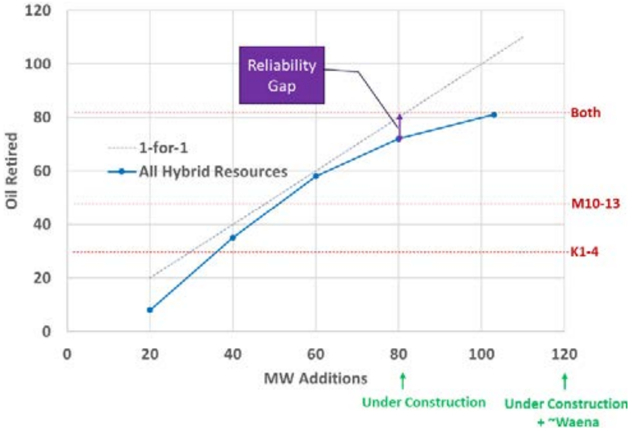

Figure 2. Reliability Frontier for retirement of oil units and additions of new resources.

There are options available to get to a reliable system with both units retired, including simply constructing more hybrid units, which are currently being tendered in HECO's Stage 3 procurement process, building the proposed 40MW Waena BESS (which was selected in the Stage 1 solicitation but does not yet have regulatory approval), adding load shifting or customer-sited resources (such as the Grid Services RFP), or other sources of generation.

In 2022 and early 2023, these results were shared with the PUC, HECO, and the Maui ACET to support ongoing planning in the state and continued monitoring of Stage 1 & 2 replacement schedules. The HNEI-Telos team plans to continue updating and refining the analysis given changes to procurement schedules, changes to load, and other system developments. Results of this work will be presented to key stakeholders when it is relevant to do so.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2023

B3: Oʻahu Retirement Study

OBJECTIVE AND SIGNIFICANCE: Oʻahu's fleet of oil-fired generators is aging, becoming increasingly unreliable, and more difficult to maintain. Increased cycling to integrate variable renewable energy and more stringent EPA emissions policies are also decreasing the longevity of these units. In September 2022, HECO retired its largest coal-fired power plant and replaced it with a portfolio of hybrid solar + storage projects. At that time, the HNEI-Telos team conducted analyses showing that solar + storage could reliably replace the coal plant. However, the ability of solar + storage to continue replacing firm capacity – resources that are available irrespective of weather – diminishes at higher levels of retirements. Given that significant amounts of firm capacity will be required to operate a reliable grid (Appendix C1), HNEI-Telos conducted longer-term analysis to help develop long-term retirement plans for Oʻahu.

KEY RESULTS: Under current load levels, the Waiau steam oil plant (370 MW) could be retired reliably, but would require 900 MW of solar and storage hybrid resources – double the amount of recent procurements. If load growth materializes as expected – largely from expected EV adoption – the same amount of solar and storage could only retire 150 MW, a small portion of the total plant. As a result, to achieve state-wide decarbonization targets, the utility needs to simultaneously plan for oil plant replacements and the growing capacity needs to support electric vehicles.

While some of the oil units can be replaced by near-term solar and storage additions, the ability to continue replacing fossil-fuel resources exclusively with hybrid solar and battery plants is limited. Other firm resources need to be considered for future planning.

BACKGROUND: HECO's oil generation plants are aging and becoming less reliable. On average, they are over 40 years old, with some plants over 60 years old – well beyond their original design life. The Waiau power plant, for example, is the third oldest non-hydro generating station over 20 MW in the United States. These old systems lack the flexibility required to integrate renewable energy sources effectively, leading to increased curtailment and increased likelihood of equipment failures.

Increased age, cycling, and emissions compliance requirements are all eroding generator reliability and availability. This trend, which started in 2015, increased further in from 2020-2022.

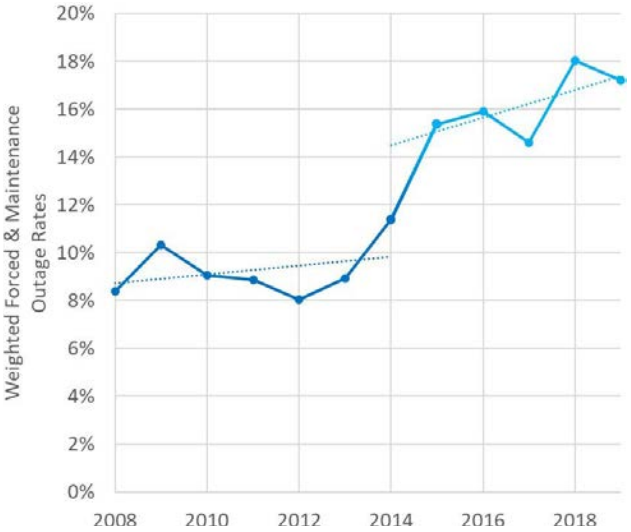

Figure 1. Increasing maintenance and forced outages for HECO's Oʻahu thermal fleet.

Some of these plants will need to be retired, but it will take years to plan, receive regulatory approval, permit, interconnect, and construct new facilities. Early and proactive planning, starting now, is essential to maintaining reliability and options in the future.

PROJECT STATUS/RESULTS: Solar and storage can effectively reduce the generation from oil plants, allowing them to run less and reduce emissions significantly. However, there are limits to how much capacity can be retired completely, while maintaining a reliable system.

To assess the retirement and replacement options available, HNEI conducted a study for Oʻahu that evaluated system reliability across hundreds of unexpected generator outages and over twenty years of weather conditions. The system was evaluated across a range of load growth, solar and storage additions, and additions of new firm capacity. The scenarios evaluated included a combination of the following parameters:

- **Load Growth**: Evaluated Base Load and High Load growth assumptions, representing a current load level and one based on a 2030-2040 load level (with the range representing the pace of electrification).

- **Solar PV and storage adoption**: Various solar and storage levels were evaluated, ranging from solar and storage levels procured in Stage 1 and 2 to an increase of 1100 MW of new projects.
- **Firm Capacity Additions**: The analysis was conducted with and without the proposed 400 MW of firm capacity additions identified in the IGP and Stage 3 Firm Renewable procurement.

Results show that recent procurements for solar and storage present further opportunities for retiring additional oil plants. However, solar and storage resources alone cannot entirely replace all of the oil plants on the system. During extended periods of low wind and solar availability, which can persist for several days, some dispatchable firm capacity is still required to maintain reliability. Moreover, the increasing adoption of electric vehicles contributes to a rise in overall load, which limits the possibilities for retiring oil plants without new dispatchable firm capacity.

Under current load levels, the Waiau steam oil plant (370 MW) could be retired reliably, but would require 900 MW of solar and storage hybrid resources – double the amount of recent procurements. If load growth materializes as expected – largely from expected EV adoption – the same amount of solar and storage could only retire 150 MW, a small portion of the total plant. As a result, to achieve state-wide decarbonization targets, the utility needs to simultaneously plan for oil plant replacements and the growing capacity needs to support electric vehicles.

Beyond the Waiau plant, there are little to no options available to retiring additional capacity (i.e. the Kahe steam oil plant), unless some other firm capacity is added to the system. Adding 400 MW of new firm capacity to the system, for example, would allow for the retirement of up to 700 MW of oil capacity depending on the amount of solar and storage added, even with continued load growth.

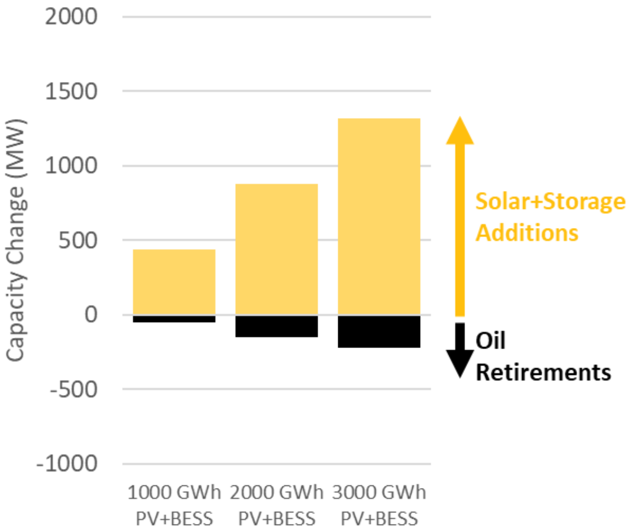

Figure 2. Solar + storage additions required and oil retirements feasible while maintaining 0.1 days/year LOLE reliability levels.

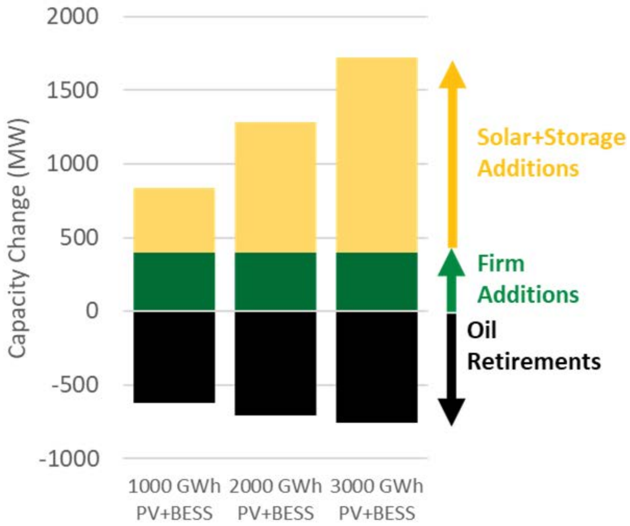

Figure 3. Solar + storage and firm renewable additions required and oil retirements feasible while maintaining 0.1 days/year LOLE reliability levels.

By creating a portfolio of solar, storage, and new clean firm capacity, much of the legacy steam oil fleet on O‘ahu can be retired. Given the continued need for firm capacity, the age of HECO’s generation fleet, and ambitious state policy related to electric vehicle adoption and other electrification efforts, prudent retirement planning is warranted. Monitoring load growth trajectories, specifically related to EV adoption is needed. In addition, any planning for new firm capacity additions should start now, as new plants will take several years for design, permitting, procurement, and interconnection. In the meantime, HECO has an opportunity to retire a few priority units while working to bring additional supply resources online.

Table 1. Solar + storage additions required to maintain reliability at various levels of oil-generator retirements.

	Solar + Storage Additions Needed		
Cumulative Retirements	**Base Load**	**High Load**	**High Load + 400 MW Firm**
Waiau 3-4 (100 MW)	100 MW	600 MW	0 MW
Waiau 5-6 (200 MW)	300 MW	1000 MW	0 MW
Waiau 7-8 (370 MW)	900 MW	N/A	0 MW
Kahe 1-2 (550 MW)	N/A	N/A	300 MW
Kahe 3-4 (700 MW)	N/A	N/A	440 MW

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

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Last Updated: November 2023

B4: Oʻahu and Maui Load Flexibility

OBJECTIVE AND SIGNIFICANCE: HECO's latest Integrated Grid Plan (IGP) relies heavily on customer-sited resources as part of the resource mix to achieve the RPS. These customer resources include significant levels of energy efficiency and rooftop solar, and increasing levels of distributed batteries, and electric vehicles. Historically, these DER resources were unobservable and uncontrollable, but new technologies and grid service programs at the utility may allow for increased customers responsiveness that can help to balance the grid, defer new capacity, and help integrate additional solar PV. The objective of this study is to quantify potential grid benefits of load flexibility and identify characteristics that are most valuable to the future grid.

KEY RESULTS: Analysis conducted by the HNEI-Telos team shows that a static daily load shifting from evening peak to mid-day, such as might be encouraged by time of use (TOU) rate, would provide limited bulk-system benefits on Oʻahu. This is because the amount of battery storage expected to be deployed over the next few years saturates the opportunity of reducing peak load and moving load to the middle of the day.

On Maui, there is a near-term capacity need and current battery proposals (Waena 40 MW BESS) are smaller than Oʻahu as a percentage of load. As a result, while load flexibility will compete with future battery storage, there is a near-term opportunity for load shifting to help maintain reliability when oil capacity is retired in 2028.

Across islands, dynamic load flexibility – that moves load throughout the day based on the day's conditions or across the week – is shown by HNEI/Telos analysis to be considerably more helpful than static load shifting for reliability purposes. This flexibility, however, would require more sophisticated controls or communication in place of, or in addition to, the current proposed TOU rate.

BACKGROUND: With advances in DER technologies and the proliferation of smart devices, customer load can adjust to better align with the capabilities of the power system. However, this load flexibility can only be leveraged if appropriate programs and rates are established to incent the behavior. The PUC and HECO are currently evaluating options for load flexibility across a variety of initiatives, including through advanced rate design (TOU rates), DER Phase 3 program design, and a competitive solicitation of grid services (i.e. Maui Grid Services RFP). While each of these programs contributes to load flexibility, each will have different impacts on the power system given the parameters and operating characteristics of the program.

In parallel, HECO is planning to retire aging oil generators and replace them with a mix of renewable energy and battery energy storage. Over the next few years, Oʻahu will be bringing online 400 MW of hybrid solar + storage plants and 185 MW of standalone storage through the Stage 1 and 2 procurements and has plans to retire 371 MW of generation at the Waiau power plant by 2030 (in addition to the 185 MW AES coal retirement in 2022).

On Maui, the Kahului K1-4 steam oil power plant is planned to retire as soon as possible and the Māʻalaea M10-M13 diesel generators may need to be retired sooner than expected due to lack of replacement parts. At the same time, hybrid solar + storage replacement resources have been delayed or cancelled due to supply chain disruptions, community opposition, and increased project costs. These challenges have led to the consideration of load flexibility as a capacity resource to replace the aging generation.

PROJECT STATUS/RESULTS: The HNEI-Telos team analyzed the benefits of load on Oʻahu and Maui. The study considered potential fuel cost savings and avoided capacity needs attributed to shifting up to 20% of evening residential load from the evening peak load period to the middle of the day. This analysis was conducted across multiple scenarios, first evaluating grid operations prior to storage additions, a near-term grid with planned solar and storage additions, and a higher solar and storage portfolio. This provides a view of changing system benefits of load flexibility relative to the amount of storage on the grid.

Oʻahu Results

In the case of fuel cost savings on Oʻahu, TOU rates have minimal benefits. The reason for this is two-fold. First, while solar generation is abundant in the middle of the day, there is limited curtailment – even before battery storage is added – and oil generation is still needed. Shifted load, therefore, is still served almost exclusively by oil generation, albeit with a modest improvement in plant efficiency (heat rate). Second, round-trip energy losses required to shift the energy (either via behind-the-meter batteries, pre-cooling of evening air conditioning, or otherwise), leads to a net increase in demand due to load shifting.

When batteries are added to the Oʻahu system, these modest benefits are reduced further as curtailment of wind and solar is largely eliminated, and there are limited fuel savings from additional load shifting.

However, TOU rates are designed, in large part, to reduce capacity needs rather than fuel savings. The power system includes many "peaking" generators that are built to run sparingly, only in times of high load and when needed for reliability. Load shifting, in theory, could reduce peak demand and avoid the need for new "peakers" or enable oil plant retirements. However, similar to fuel cost savings, the peak capacity needs on Oʻahu are also being addressed with battery storage additions.

To quantify the capacity impact, the study implemented a sequential Monte Carlo probabilistic model which incorporates 22 years of chronological solar data, 8 years of chronological wind data, and hundreds of samples of thermal generator outages to quantify the resource adequacy of both Oʻahu and Maui. This process was used to test if the power system is reliable across a variety of conditions, including unexpected generator failures or low wind and solar conditions. The expected unserved energy (EUE) measures the likelihood of having insufficient resources to serve load and the potential for rolling blackouts.

The results show how TOU rates that discourage energy use from 5pm - 9pm can effectively mitigate reliability risk prior to battery storage additions ("Recent Past"), but would not meaningfully help after grid-scale batteries are added ("Near Future"). This is because the remaining reliability risk is spread evenly across the day and the remaining capacity need is no longer isolated to evening peak demand hours. In other words, there is less of a "peaking" need.

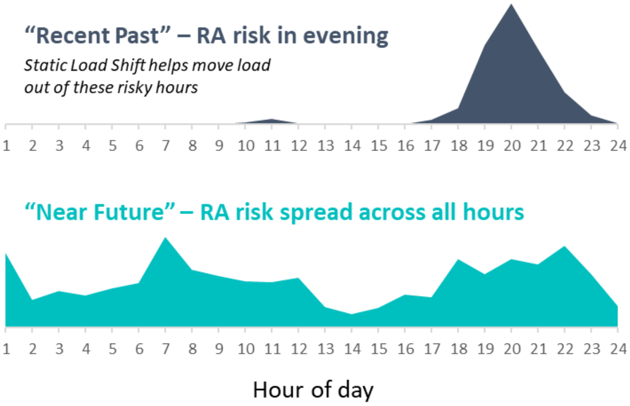

Figure 1. Distribution of EUE by time of day.

Maui Results

On Maui, where the near-term resource mix does not yet include large amounts of energy storage, load flexibility can be part of the mix to retire oil generation, but competes directly with grid-scale battery storage additions that are planned with the Stage 1, Stage 2, and Stage 3 procurements. Furthermore, the type of load flexibility could have a significant impact on the reliability of the system.

Currently, there is approximately 80 MW of hybrid solar + storage additions under construction on Maui. These additions would be enough to retire K1-4 or M10-13, but not all 81 MW of generation across the two existing power plants. To address the gap in reliability from that remains from only adding 80 MW of hybrid resources, various types of load flexibility were assessed for their resource adequacy benefits, or loss of load expectation (LOLE). LOLE assesses the resource adequacy of power systems under various system conditions by using a probabilistic resource adequacy methodology. This is the same probabilistic methodology used to evaluate the AES coal plant retirement on Oʻahu (Appendix B1). The results of which are shown in Figure 3 across a range of potential mitigation options.

Several load flexibility options were considered, a general time of use rate "Static Load Shifting (TOU)," a dynamic, controllable DER program ("Grid Services RFP"), grid-scale standalone storage ("20 MW BESS"), and through "Daily Managed EV Charging." These options were differentiated in the following way:

- The Grid Services RFP is modeled as a 20 MW resource that can only contribute for 2 consecutive hours during specific times of the day. It also has 10% energy losses and must charge during the daytime hours.

- The Static Load Shifting (TOU) is modeled as a 20 MW resource that moves roughly 75 MWh from the 5-9pm peak into the daytime and overnight hours.
- Battery energy storage is modeled as a 20 MW resource that is fully controllable by the grid operator, subject to energy limitations and round-trip efficiency losses.
- Lastly, for reference a 20 MW perfect generator was considered, with no energy limitations or outage rates.

Results show that 20 MW of load flexibility is comparable to the capacity grid services provided by a standalone storage resource, but that a hybrid resource (which also brings additional energy) and a perfect capacity resource are more beneficial.

Another sensitivity was run that assessed load flexibility throughout the week. This type of intra-week load flexibility was shown to improve LOLE by 90+% depending on the scenario on both Oʻahu and Maui. Intra-Week load flexibility behaves like long-duration storage in this regard.

The findings indicate that load flexibility can capture some of the energy arbitrage value that batteries provide, improving resource adequacy. Effectively, the energy arbitrage benefit is quickly saturated by whichever resource (Load Shifting or batteries) arrives first.

HNEI plans to continue to refine this analysis, with the goal of supporting decision makers at the PUC and HECO as they continue to design customer programs to support evolving grid needs. HNEI hopes to assess the value of load flexibility in deferring distribution grid upgrades in a future version of this analysis.

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

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Last Updated: November 2023

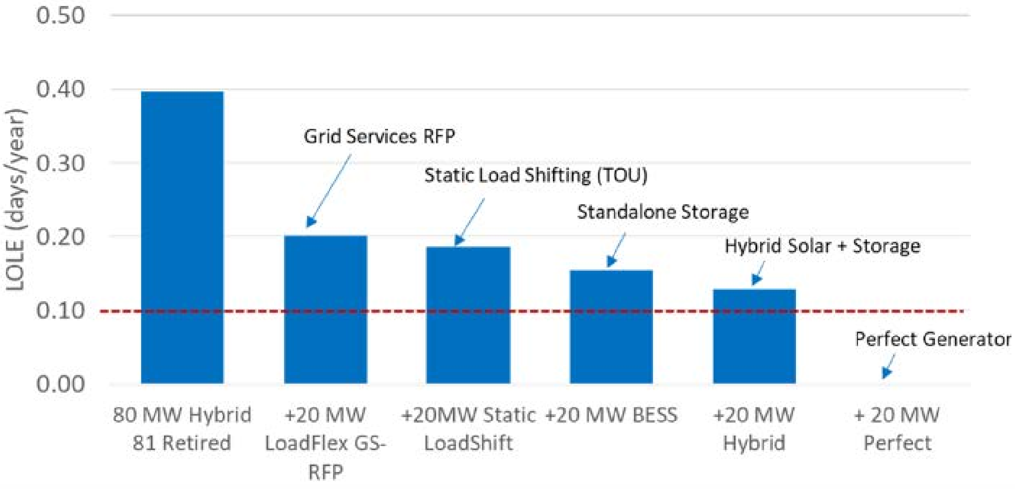

Figure 2. Loss of load expectation (LOLE) in days per year with different load flexibility options.

C1: Clean Firm Needs

OBJECTIVE AND SIGNIFICANCE: This study was intended to help inform and frame the ongoing discussions and planning related to the need of dispatchable firm capacity. The objective is to inform future procurement and potential legislation for both variable and firm renewable energy. The analysis sought to determine the minimum amount of firm capacity that the system would require – at various levels of wind, solar, and storage – to maintain adequate generation resources during periods of extended poor weather. This analysis also evaluated what levels of variable renewable energy can be implemented without impacting (shutting the door) on future options. This information can be used to inform decisions on oil-fired power plant retirements, guide procurement of new resources, and to quantify challenges of relying solely on variable renewable energy and storage alone for a 100% renewable grid.

KEY RESULTS: The findings of this analysis indicate that on Oʻahu, even in a very high variable renewable energy and storage grid, there is a need for very significant amounts of firm capacity, up to 600-750 MW. In this future clean energy system with very high penetration of variable renewables, these resources would only need to run sparingly, but are essential for reliability. When they are necessary, it could be for multiple consecutive days at a time making it difficult, if not impossible, to solve the reliability challenge by exclusively relying on variable renewables and battery storage, even long term storage. Today, this grid service is provided by the existing HECO oil plants. These plants are aging and becoming less reliable and cannot be converted to meet the state's 100% renewable energy target. At some point, they will need to be retired and replaced with other forms of firm renewable energy.

The analysis for Oʻahu was extended to each of the other islands to compare the total firm capacity need and operational characteristics of these resources. Results for the state confirm that firm capacity needs are approximately 50% of peak load for all the islands.

BACKGROUND: Despite the growth in wind, solar, and battery technologies over the past ten years, there is increased interest in firm renewable energy technologies in Hawaiʻi and the power industry in general. This is being driven by several factors, including resource saturation, resource diversity, reliability, and agricultural and forestry sector objectives. Dispatchable firm capacity refers to power generation that is available for a sustained period of time, irrespective of weather conditions or the availability of wind and solar resources.

In the 2022 legislative session, the Hawaiʻi State Senate and House of Representatives introduced a series of bills that sought to promote – and in some cases mandate – increased adoption of firm renewable energy. For example, HB 1611 and SB 2510 proposed to establish a state energy policy that requires at least 33.3% of renewable energy be generated by firm renewable energy. These bills also proposed to limit the percentage of any one type of renewable energy source to 45% of all generation for each island, except for geothermal generated energy. It was unclear if the intent of this requirement was to limit the percentage of distributed PV and utility-scale PV to 45%, but since some of the islands already have high levels of these resources, it could prevent the installation of additional solar systems. These bills were approved by both the Senate and the House, but later vetoed by the governor. While these laws are not in statute today, there is continued interest in firm renewable energy and likely will be the topic of future legislative sessions.

In addition, on March 1, 2022, Hawaiian Electric (HECO) issued a request for proposals (RFP) seeking proposals to acquire 500 to 700 megawatts of energy from firm renewable generation resources on Oʻahu with a targeted online date between 2029 and 2033. According to HECO, "while solar and wind energy resources will help us hit our near-term clean energy milestones, we'll also need firm renewable resources available for customers when the sun isn't shining, or the wind isn't blowing."

The RFP also states that the objective of the firm renewable procurement is to ensure that "sufficient firm capacity must be available during periods of low wind and solar production. Modernizing the ageing fossil fuel generation fleet (some of which are over 75 years old) by adding new renewable firm generation is consistent with decarbonization goals and policies as new firm generators will be installed alongside significant quantities of low-cost renewables to ensure reliability and resilience, resulting in overall reductions in carbon emissions.”

There is also increased attention being afforded to the role of hydrogen in decarbonizing the Hawaiʻi energy sector, including for electric power uses (Appendix C2) along with locally sourced biomass and/or biodiesel, and potentially the development of new geothermal resources.

PROJECT STATUS/RESULTS: Given the recent legislative actions and proposed firm renewable procurements by the utility, HNEI conducted a series of analyses to identify the amount of firm renewable capacity that may be required in Hawaiʻi. The analysis was first conducted for Oʻahu and the methodology was later extended to the islands of Kauaʻi, Maui, Molokaʻi, Lānaʻi, and Hawaiʻi.

To quantify potential firm renewable needs, the study team developed a simplified screening methodology and then verified the results with robust probabilistic resource adequacy and detailed operational modeling of a specific resource mix. The screening methodology was conducted in a five-step process, illustrated in Figure 1.

The study team developed a small number of potential future resource mixes that reach or exceed 90% renewable energy, by varying the amount of solar + storage and offshore wind resources that are proposed to be available. This step was done at increasing levels of available wind and solar resources. Using Oʻahu as an example, resources were added in 1,000 GWh per year intervals. These scenarios were then evaluated without the existing oil capacity on the system, to calculate the remaining amount of capacity and energy needed after accounting for solar, wind, and battery energy storage. These units were replaced with blocks of perfectly available and flexible capacity – which would operate in a manner to limit total capacity additions while meeting the needs of the system.

The scenarios and perfect capacity resources were modeled across 21-years of weather resources (which represented historical weather conditions from 1998-2018) for the solar and offshore wind resources. The model was evaluated across all hours of the year in the 21-year period, creating dispatch profiles for nearly 184,000 hours of chronological operations, illustrated in Figure 2. The use of multiple years of resource for this analysis, inherently considers the impact of historic periods of low resource.

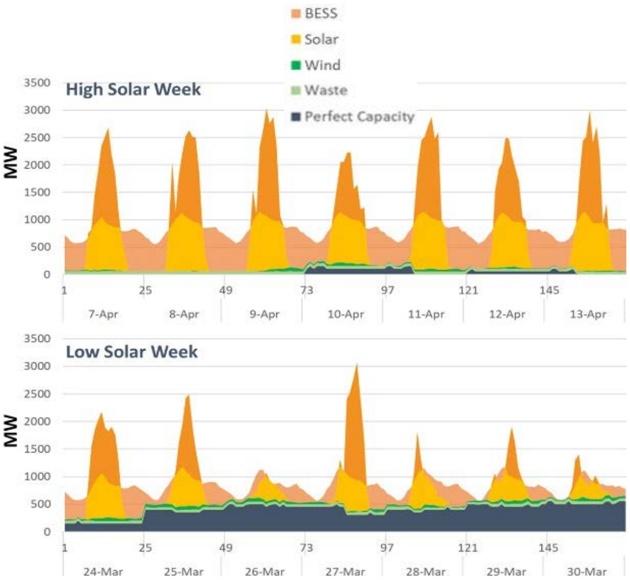

Figure 2. Representative high and low solar weeks and the need for firm renewables.

The results of the simulations were used to quantify system performance and firm renewable capacity needs. In particular, the metrics resulting from this analysis included the amount of curtailment of variable wind and solar resources, as well as the utilization of the perfect capacity resource. For the perfect capacity resource, particular attention was given to the maximum dispatch of the unit, which implies the overall capacity need. Operational metrics like number of starts, ramp needs, operating hours, and capacity factor by incremental block were also evaluated. Cost metrics were also incorporated as proxy values for the perfect capacity resource – as if it was provided by the existing oil-fired generating

Figure 1. Five-step screening methodology to calculate firm renewable needs.

mix or a future firm renewable resource mix such as biodiesel.

Results of the analysis are provided in Figure 3, showing several islands firm capacity requirement as a percentage of peak load (y-axis) at varying levels of solar and storage builds (x-axis). Only the maximum dispatch of the perfect capacity resource is shown as a percent of system peak load – illustrating the aggregate *capacity* need of 40-50% of peak load – depending on the amount of variable renewable energy and battery energy storage on the system. These values can be used as a proxy for the firm renewable resource needs of the system. This clearly shows the relationship between increasing variable renewables and storage capacity to the diminishing needs for firm renewable capacity.

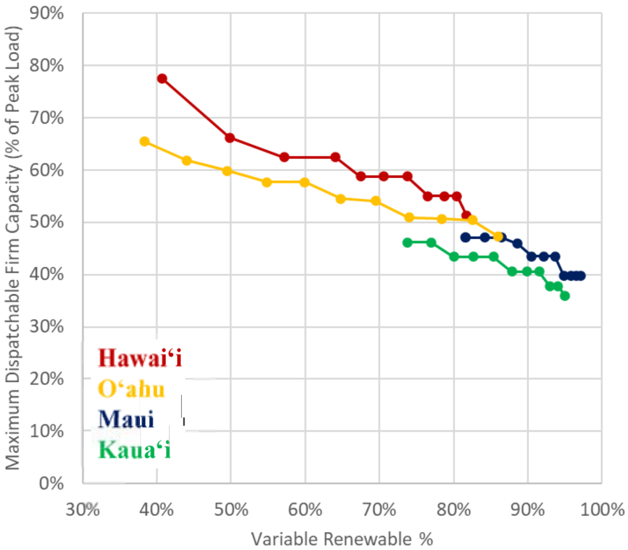

Figure 3. Firm capacity needs at increasing levels of variable renewable energy (PV+BESS) across islands.

However, the analysis also showed that even at very high penetrations of variable renewable energy – reaching almost 95% of annual energy – there is still a substantial need for firm capacity. This is approximately 50% of the system's peak demand and emphasizes the point discussed previously that there are diminishing returns associated with additional variable renewable energy at high penetrations.

The analysis was repeated at various levels of electric vehicle penetration. The results for Oʻahu indicate that a 20% increase in EV charging during peak demand periods would only increase the firm renewable requirement by approximately 50 MW, and would increase by approximately 250 MW with the 60% EV peak charging scenario. In addition, these peak demand needs were only modestly changed by differences if different charging profiles were implemented. While daytime charging is slightly better than peak demand or overnight charging profiles, there is relatively little difference between the time of charging and the additional firm renewable capacity needed.

The reason for this is twofold; first, the system is largely energy constrained rather than capacity constrained. As a result, the firm renewable needs are largely driven by low wind and solar days rather than hourly demand. Second, there is a significant amount of grid battery energy storage assumed in these portfolios, and thus plenty of flexibility to move energy from one time of day to another. Overall, while EV adoption rates would change the total amount of renewable energy needed to reach the state's renewable energy targets, the timing of EV charging has a relatively modest impact on overall firm renewable needs for reliability.

Today, there are limited zero emission resources available to provide dispatchable firm capacity, and each has limitations that must be considered. Biomass and biodiesel, even if run sparingly, would require large feedstocks exceeding available land use and requiring imported fuels. Geothermal is available on Hawaiʻi Island, but would likely require subsea, interisland cables for Oʻahu and Maui. Hydrogen and other forms of multi-day storage could also provide firm capacity, but would exacerbate land use challenges, community acceptance, and costs remain highly uncertain.

In addition, these options are all significantly more expensive and more uncertain, than near-term additions of solar, wind, and battery energy storage. While these resources will not eliminate the need for firm resources (currently provided by oil capacity), they will diminish the need while increasing renewable energy and CO_2 emissions in the near-term. These additions also do not close the door on future options if new technologies or firm renewable resources become available.

This study is intended to be a screening analysis of the potential firm renewable needs for the future O‘ahu system and to help inform proposed legislation and utility procurements. In light of the Hawai‘i State Legislature’s efforts – through SB 2510 – to require a minimum amount of firm renewable energy, ongoing work will be continued by HNEI to inform on the appropriate levels of firm renewables that may be required. In addition, as the utility’s Stage 3 RFP and Firm Renewable RFP continue to progress, additional analysis can be conducted on specific portfolios and resource types.

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

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Last Updated: November 2023

C2: Hawaiʻi Hydrogen Integration Study

OBJECTIVE AND SIGNIFICANCE: Act 140 "Relating to the Hawaiʻi Hydrogen Strategic Plan" of the 2022 Hawaiʻi State Legislature tasked HNEI to "examine the potential for the production and use of renewable hydrogen in the State and the potential role of renewable hydrogen in achieving a local, affordable, reliable, and decarbonized energy system and economy." Results of this study are being finalized and will be submitted to the legislature ahead of the 2024 session.

In conducting this study, HNEI sought to identify and quantify the potential uses for hydrogen (H_2) in Hawaiʻi and to quantify the potential to produce hydrogen locally to meet those potential uses. Based on a conservative estimate for hydrogen use in Hawaiʻi, the required materials, energy, water, land, and infrastructure needed to serve that demand are quantified. These analysis are intended to determine the feasibility of large-scale hydrogen production and use across the state and whether Hawaiʻi can play the role of a hydrogen exporter.

KEY RESULTS: Results of this analysis show that while there is a potential for hydrogen to reduce the carbon intensity of some end uses, it is not likely to make a significant contribution to Hawaiʻi's decarbonization efforts. With limited production potential on Oʻahu relative to potential demand, the cost and difficulty of interisland transport of hydrogen further limits its decarbonization potential.

Producing hydrogen using electrolysis is extremely energy intensive. Given the ongoing challenges of siting new renewable resources to meet existing electric power needs, the ability to develop sufficient renewable energy sources solely for hydrogen production to offset meaningful quantities of oil imports is likely infeasible with land use constraints and community acceptance being significant factors. Stated another way, while there is an opportunity for some business development around the production and use of hydrogen, it is unlikely to contribute to a meaningful reduction in our GHG emissions, outside niche sectors.

BACKGROUND: During the 2022 legislative session, multiple bills were proposed to encourage the development of an H_2 industry in Hawaiʻi. HB 1611 proposed a State Energy Plan that specifically addressed firm renewable options, including H_2, across Hawaiʻi. HB 1937 requested that HNEI develop a H_2 strategic plan for Hawaiʻi, which examined the State's ability to advance hydrogen production from local renewable energy resources. The study shall consider hydrogen availability and feasibility locally, water usage, costs/benefits, identify end-use markets, permitting requirements, hydrogen for transportation and grid, techno-economic feasibility, and environmental benefits for resiliency, and include a comparison to imported hydrogen.

The interest in Hawaiʻi for large-scale hydrogen production and use was further elevated by passage of the Inflation Reduction Act and the expectation of significant federal funding for a national network of hydrogen hubs intended to decarbonize "hard to abate" sectors including chemical (ammonia, steel, cement), transportation (long-haul trucking), and power (long-duration storage) sectors.

Beginning in 2022 and continuing through much of 2023, multiple stakeholders in Hawaiʻi were actively pursuing DOE funding for a local "hydrogen hub" in the state. While Hawaiʻi's Hub proposal identified sufficient production potential to meet DOE proposal requirements, to our knowledge, there has not been a study to quantify and identify the means to produce the quantities of hydrogen needed to decarbonize the Hawaiʻi energy economy. Additionally, we are not aware of any assessment of integrating hydrogen production in a high variable renewable energy grid. This study will serve as an initial basis for future hydrogen analysis in Hawaiʻi as decarbonization goals progress.

While many stakeholders have identified and discussed potential uses for green hydrogen, little has been done to analyze: 1) the electricity required for its production, 2) the storage that may be necessary for implementation of a practical system, or 3) the full life-cycle cost associated with producing and using hydrogen in Hawaiʻi. As part of this assessment under Act 140, the HNEI-Telos team conducted a detailed analysis to identify high-priority use cases, quantify the scale of potential hydrogen and electrolysis needs, and to simulate the production and storage requirements.

PROJECT STATUS/RESULTS: A review of the potential hydrogen demand by end use has been completed and informs the basis of assessing how Hawai‘i can meet the expected demand via local resources. The transportation and electric power sectors make up the bulk of petroleum usage in Hawai‘i, offering potential markets for hydrogen, but competition from direct electrification must be considered. Disaggregating the end-use sectors into more granular energy uses, such as shown in Figure 1, is required to assess electrification versus H_2 potential.

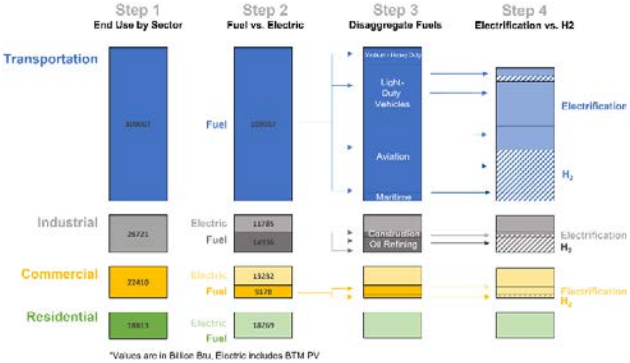

Figure 1. Example of the disaggregation of end use sector energy input into electrification versus H_2.

Based on an evaluation of potential end uses, the HNEI-Telos team identified four uses as being the most technologically mature with the potential for near-term deployment if clean hydrogen is available. These are:

- ***Aviation***: Production of sustainable aviation fuel (SAF) using hydrogen;
- ***Medium/heavy duty vehicles***: Buses and trucks, primarily those that need longer range are potential markets for hydrogen powered vehicles, although this application could be challenged by continued advancements in battery technology;
- ***Electric power***: Hawai‘i’s grids will need firm dispatchable power and seasonal storage to ensure grid reliability with high penetration of variable renewable generation; hydrogen for this application may be challenged by developments in long duration battery storage, biofuels, and advanced geothermal; and
- ***Oil refining/chemical processes***: Residual petroleum processing and industrial producers, such as Hawai‘i Gas, may have increased future hydrogen demand.

Based on this assessment, the end uses most likely to incorporate hydrogen were quantified using existing plans or by assuming a meaningful penetration of hydrogen use. Electric power needs were based on meeting the firm fuel needs for 2045 shown in HECO’s IGP plan, which is approximately 5% of electric energy. This assessment provides a meaningful scale of hydrogen use to inform the feasibility of producing quantities sufficiently large enough to benefit our energy systems.

Based on the penetration levels shown in column 2 of Table 1, the demand for H_2 was calculated.

Table 1. Act 140 study hydrogen end use estimate assumptions.

H_2 End Uses	H_2 Need Assumption	H_2 Mass Required (kg)
Ground Transportation	20% Trucks & 10% Buses	262,727,245
Aviation (SAF)	10% of annual jet fuel	15,067,000
Electric Power	5% of annual energy	37,894,099
Industrial (Hawai‘i Gas)	15% hydrogen in pipeline	839,500

Under the Act 140 study, the feedstock and energy requirements for producing hydrogen were assessed for each island by assuming production via biomass gasification or water electrolysis using renewable energy. Both of these methods require significant quantities of materials, energy, and land. Generally accepted values for conversion of organic feedstock or water into hydrogen (Table 2) were used to quantify the total input requirements.

Table 2. Conversion values for biomass gasification and water electrolysis to produce hydrogen.

H_2 Production Method	Conversion Factor
Gasification of Waste	13-20 kg waste/kg H_2
Gasification of Crops	10.5 kg biomass/kg H_2
Water Electrolysis	55 kWh/kg H_2

These conversion efficiencies with potential island by island demand were used to determine the capability of each island (O‘ahu, Hawai‘i, Maui, and Kaua‘i) to produce hydrogen to meet its own needs.
As the most populous island, O‘ahu would have potential markets for the largest amount of hydrogen

(64% of demand), which poses unique challenges since Oʻahu also has the lowest hydrogen production potential due to land constraints.

For H_2 production using renewable energy for water electrolysis, results indicate that in order to meet the estimated demand for hydrogen the statewide 2045 projected energy required (18,137 GWh) would need to more than double. Put another way, Hawaiʻi would need to double its projected future electricity production to produce the equivalent of 326 million gallons of gasoline to meet demand (Tables 1 and 3). This scale issue is the most significant barrier to hydrogen playing more than a marginal role in decarbonizing Hawaiʻi.

Table 3. Water electrolysis energy requirement to serve estimated hydrogen demand by island.

Island	Estimated H_2 Demand (kg/yr)	Energy Required (GWh/yr)
Oʻahu	207,153,703	11,507
Hawaiʻi	57,006,330	3,166
Maui	44,665,492	2,481
Kauaʻi	17,702,323	983
Total	326,527,848	18,137

While hydrogen has limited potential for decarbonizing the Hawaiʻi economy, the uses that have been identified represent significant opportunity for local business development. To inform this potential, the HNEI-Telos team then assessed production costs, storage, on-island transportation/storage needs, and inter-island shipping from Hawaiʻi Island to Oʻahu. To support this work, we also conducted detailed grid modeling using the 2045 IGP portfolio integrated with electrolyzers to provide hydrogen for 5% of each island's annual electricity demand.

Several electrolysis integration pathways were modeled to investigate different grid integration and production challenges for H_2 to serve electric power needs. These included:

- **No H_2 Resources**: the electrolyzer is added to the 2045 IGP grid with no additional resources, providing hydrogen only when there is surplus energy on the grid and battery storage is full;
- **Self-supply**: electrolyzers are powered by a separate portfolio of renewable energy resources and does not operate with the grid; and
- **Grid-supply**: the electrolyzers are powered by a separate portfolio of renewable energy resources, but those resources are integrated with the grid to also absorb curtailed energy.

Initial results of the grid analysis for the 2045 portfolio shows that water electrolysis can utilize a significant amount of the curtailed energy, but it is not sufficient to meet the 5% of electricity target. Additional renewable energy resources dedicated to hydrogen production are required to provide enough hydrogen to meet the 5% firm power need.

Results also indicate that using H_2 for electric power needs will require large-scale storage that would shift hydrogen seasonally. This poses a potential challenge due to large-scale infrastructure requirements where utilization will occur only during a few months of the year. The inclusion of additional end use demand in the next steps may alleviate this issue since storage would be used for multiple purposes.

The H_2 integration study will determine the operational requirements for future H_2 load to serve multiple purposes in the Hawaiʻi energy economy and will inform the community on the feasibility of integrating large-scale hydrogen production using electrolysis and renewables. The study is expected to answer a number of important questions, such as:

- How much H_2 storage is required to meet H_2 end-use demands? How much storage would be required for long duration energy storage?
- What impact does H_2 load have on statewide electricity curtailments?
- How much additional renewable energy is required to serve H_2 production?
- What amount of load flexibility is useful from H_2 electrolyzers?
- What are the system losses and roundtrip efficiency of the H_2 system, inclusive of production, transportation, and storage of H_2 within the island?
- What impact will these potential hydrogen markets have on Hawaiʻi's GHG emissions?

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2023

C3: Long Duration Storage Modeling

OBJECTIVE AND SIGNIFICANCE: In Hawaiʻi and across much of the country, significant attention is being given to identifying the need and amount of clean firm renewable energy required for a 100% clean electricity grid. While much attention has been afforded to hydrogen and/or biodiesel resources to fill this need, recent developments in long duration, multi-day battery energy storage may be another option to provide sufficient firm renewable capacity to bridge extended periods of low solar and wind resource. To evaluate this potential, the HNEI-Telos team conducted a limited evaluation to determine whether long-duration storage can provide the required resource adequacy and capacity.

KEY RESULTS: Preliminary analysis has identified two key findings. The first is that multi-day battery energy storage requires new modeling techniques. Such methods that are currently being developed by HNEI-Telos and the broader industry. The second is that, despite the long duration of discharge capability, the multi-day storage will likely be constrained to charge during periods of tight-supply – thus diminishing the efficacy of providing comparable firm capacity benefits as a thermal resource.

BACKGROUND: Under other tasks, the HNEI-Telos team has conducted significant analysis to quantify the amount of clean firm resources necessary to maintain reliability in a high renewable power system. This analysis was conducted using generic assumptions associated with a "perfect capacity" resource that is always available when needed (Appendix C1).

To date, all of the battery storage systems being integrated in Hawaiʻi are relatively short duration, capable of providing their rated output for only a few hours. Early battery adoptions on Oʻahu, Maui, and the Big Island were less than 30-minutes in duration, providing only grid services to balance fluctuations in wind output. More recent battery additions were 4-hour resources, often combined with solar projects, and added the ability to shift solar generation from mid-day to overnight periods.

However, new storage technologies are under development across the power industry that are advancing the capabilities associated with longer duration batteries. Most notably, Form Energy is currently offering a 100-hour iron battery storage product – potentially allowing for surplus renewable generation to shift across days or even weeks.

In 2022, HECO initiated its Stage 3 procurement process and specifically requested bids for 500-700 MW of firm renewable resources. This procurement, however, specifically *excludes* the option for multi-day battery storage projects regardless of their duration because of requirements around fuel storage and recharging constraints.

This analysis was conducted to understand the technical capabilities of multi-day storage resources, to develop new modeling methods, and to understand whether or not multi-day battery storage provides similar characteristics as a thermal resource with liquid fuel capabilities.

PROJECT STATUS/RESULTS: The HNEI-Telos team is currently conducting the multi-day storage analysis and anticipate having final results to share with relevant stakeholders in early 2024. Initial analysis was conducted to develop new methodologies for evaluating multi-day storage resources. This was required to overcome modeling challenges associated with foresight and predictability of multi-day storage needs.

Without foresight of the need included in the model, the battery will discharge completely and will not recharge because round-trip efficiency losses are so high. However, with perfect foresight, the model over-optimizes the long-duration storage, perfectly aligning future state of charge with grid needs. For example, the battery will charge in the days and weeks leading up to a period with sustained low renewable output and high generator outage conditions. Both outcomes misrepresent the capabilities of multi-day storage.

As a result, a new methodology was developed incorporating different forecast "look-ahead" periods in the model combined with a new constraint that requires the multi-day storage to be at or above a certain state of charge at all times, unless it is needed for grid reliability. This additional energy reserve ensures that the multi-day storage is available when needed, but does not overstate the predictability of when those events may occur. The HNEI-Telos team is currently testing different levels of these model parameters and collaborating with multi-day storage technology providers in industry to ensure the modeling process is robust.

Initial results suggest that the multi-day storage does not provide comparable benefits for reliability when compared to a thermal, liquid-fuel generating resource. This is because the future Oʻahu grid is highly energy constrained and there may be extended periods of time where the multi-day storage cannot recharge. This increases the potential for an event where the battery storage cannot recharge and redeploy fast enough to be available for subsequent grid reliability events. The energy challenge is amplified by low round-trip efficiency associated with current multi-day battery technologies.

Additional research is being conducted to adjust modeling constraints to properly reflect grid operations with multi-day storage and the evaluation of multiple grid portfolios with various solar and thermal resources to understand if multi-day storage can be integrated alongside other firm renewable resources.

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

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Last Updated: November 2023

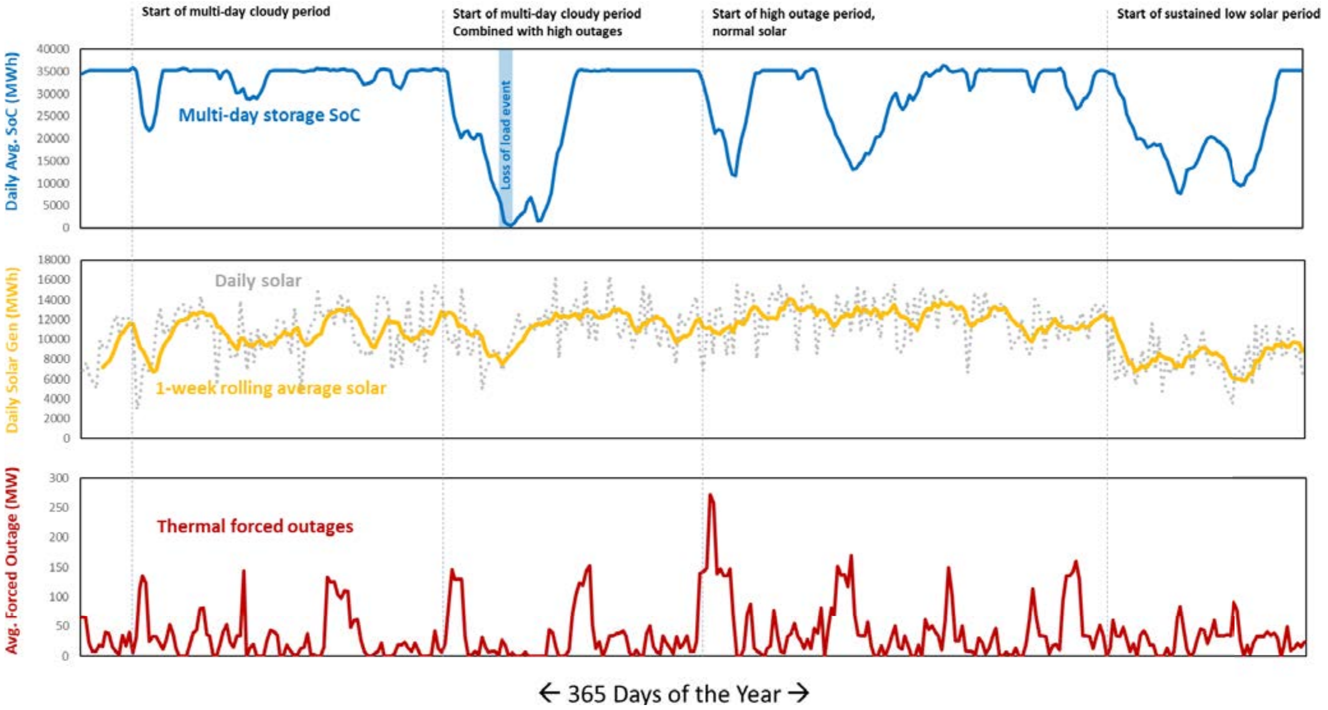

Figure 1. Modeling of multi-day battery storage state of charge (top) against Oʻahu solar resource (middle) and thermal generator outages (bottom), with loss of load events highlighted.

Appendix C: Future Energy Systems

C4: Analysis of Bill Impacts and Equity of Time-of-Use Rate Design

OBJECTIVE AND SIGNIFICANCE: Time-of-use (TOU) rates – electric rates that vary in price based on the time of consumption – are currently being developed and implemented by HECO and the Hawai‘i PUC. Under the new rate structure, electricity prices during evening peak demand periods would be three times more expensive than in the middle of the day. The intent of these rates is encourage customers to shift load to hours when solar generation is plentiful and out of peak demand hours, which have been historically more expensive. In theory, this would save customers money while also benefiting the grid and Hawai‘i as a whole through increased solar integration, reduced oil consumption, and avoided grid upgrades. The objective of this study is to assess whether the proposed rates would equitable, calculate bill impacts of proposed rates, and evaluate potential changes to revenue and cost allocation. The results of this study were briefed to HECO and made available to PUC.

KEY RESULTS: The HNEI-Telos team reviewed individual 15-minute advanced metering data across 60,000 customers for a single month. The results showed that large proportions (85+%) of non-PV customers would be Structural Winners – those who would get a cheaper bill just from switching to TOU rates, even without changing their behavior. Customers with PV, in contrast, would see a significant increase in monthly bills (62% or $82/month on average) if they were required to switch to TOU rates. Previous analysis, discussed in Appendix B4, shows that even if the TOU rate successfully encourages behavior change, it provides only limited or modest system benefits because much of the load shifting benefits are provided by grid-scale battery storage systems. **As a result, TOU-induced behavior change, as currently constructed, does not provide a meaningful reliability benefit to the grid.** Instead, TOU rates should be designed to move load across days or to mitigate distribution level constraints.

BACKGROUND: TOU rates, like those currently being proposed were first implemented by HECO in 2012 (TOU-R) and the power system has changed remarkably since then, changing the type of load shifting needed. From 2023-2025, each of the HECO grids will see a large increase in battery storage – both in standalone projects as well as utility-scale solar + storage hybrid projects. These batteries will provide much of the load shifting needs on the system, reducing the need for TOU rates.

HECO and the PUC have already committed to large battery projects in recent procurements and most of them are either already operating or under construction. These batteries provide much of the load shifting needs on the system, reducing the need for additional load shifting from TOU rates for the foreseeable future. On O‘ahu, for example, battery storage will soon reach 400 MW of capacity, over

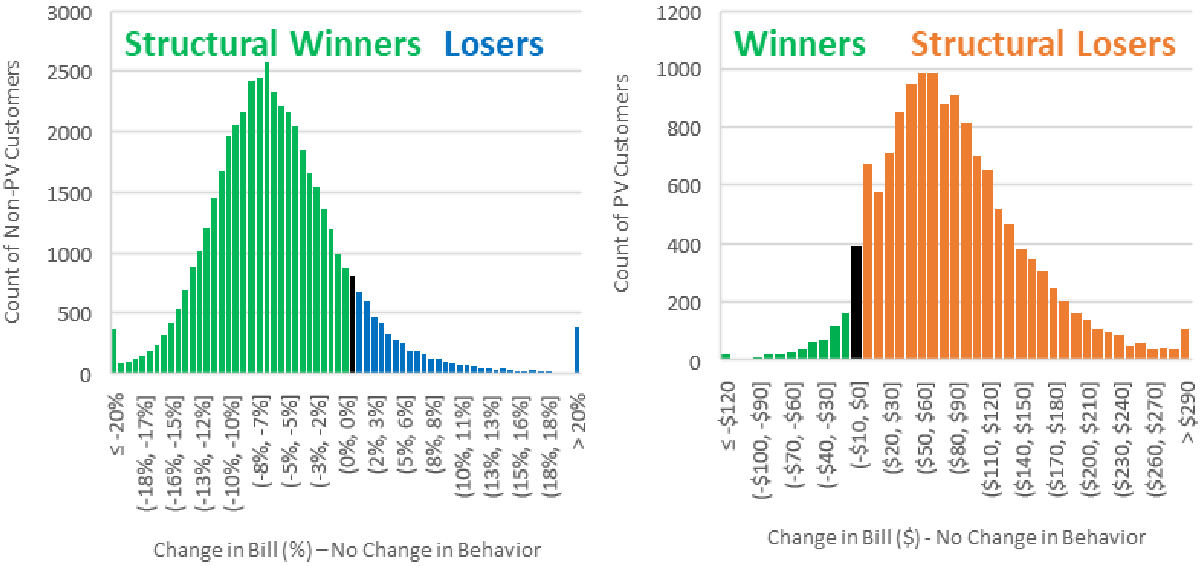

Figure 1. Distribution of bill impacts by non PV customers (left) and PV customers (right).

one-third of evening peak load, with more coming in near-term procurements. The storage deployment on other islands is even more pronounced on a proportional basis – reaching 60% of peak demand on Maui and 40% on Hawai'i Island, with additional storage coming shortly after.

PROJECT STATUS/RESULTS: The results show that while TOU rates will have only limited system reliability benefits, they will create significant changes to the way electricity is billed, and potentially create equity concerns. This could arise if some ratepayers switch to TOU rates to reduce their bill, but the load shift does not have meaningful economic benefits that can be realized by other ratepayers.

To evaluate this further, the study assessed individual customer impacts of the proposed TOU rates. The study found that most non-PV customers would save money by switching to the rate without changing their behavior. The opposite is true for PV customers – they would mostly have to pay more if a switch to TOU is required.

These findings are highly sensitive to the base daytime rate. Increasing the base rate by just one cent (from the proposed $0.19/kWh to $0.20/kWh) would significantly decrease the number of structural winners. In fact, this change would make more structural losers than winners.

These large changes in how electricity is billed should be carefully evaluated for their revenue neutrality. Assuming that Structural Benefiters switch to the appropriate rate for them, non-PV residential customers' total revenue would **drop 1.8% and disproportionately helps high energy users** without a change in behavior. Put simply, TOU rates introduce a long-term risk of revenue collection for grid services.

This analysis was paired with the Load Flexibility modeling effort to develop recommendations for the future of demand side programs in islands systems with high amounts of battery storage. While the analysis showed limited benefits of TOU rates once battery storage is added to the system, there are other opportunities for load flexibility. Principally, as is shown in the Maui load flexibility analysis, there is an opportunity for load shifting induced from TOU rates to capture the energy arbitrage value that batteries could provide. Effectively, the energy arbitrage benefit is saturated by whichever resource (load shifting or batteries) arrives first.

Given that HECO has already contracted and is currently commissioning a large number of grid-scale batteries in the Stage 1 and Stage 2 procurements, it is likely that most short-duration load shifting benefits will already be accrued to battery storage before meaningful amounts of load flexibility can be recognized.

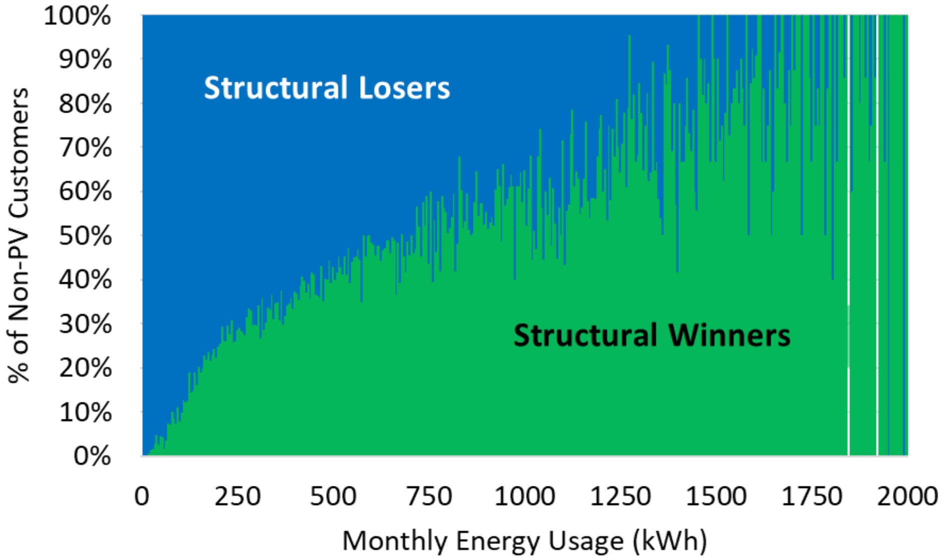

Figure 2. Percentage of structural winners vs. structural losers with TOU rates, by monthly consumption level.

Regardless of the battery deployment schedule, value was identified in load flexibility programs that modified load consumption based on changing system conditions rather than a set schedule. However, such a rate would require more sophistication – from customers, technology providers, and HECO – to implement.

The analysis evaluated potential benefits of these more sophisticated controls, which showed 50% improvement in capacity benefits when load flexibility could be dispatched according to the specific day's needs. This increased to a 95% improvement when load could be flexible across a week, shifting load out of one day (i.e. a cloudy day) and into another altogether (i.e. a sunny day).

A second option to achieve this multi-day flexibility would introduce a day of week billing (or a "Cloudy Day Rate") that effectively prices consumption higher during low solar days to incent load reduction when generation would be strained. This however would only apply to some loads, potentially some electric vehicle charging, large industrial loads, water pumping, or other schedulable processes.

Finally, rates designed to avoid distribution-network upgrades may also provide significant benefits. Rather than provide broad, system-level benefits, load flexibility could target individual distribution circuit needs. This could potentially avoid costly upgrades often attributed to solar PV additions, concentrated EV charging, or new developments. This would again require either direct load control or a more tailored rate schedule unique to each circuit.

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

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Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix C: Future Energy Systems

C5: Modeling and Validating Indoor Air Quality in Hawaiʻi Classrooms

OBJECTIVE AND SIGNIFICANCE: In recent years, especially since COVID, there has been increased attention focused on indoor air quality. Under this project, HNEI contracted Miller Kelley Architects (MKThink) to evaluate room air quality under different use cases and different ventilation typologies. Simulated and measured carbon dioxide (CO_2) concentrations were used as a metric for air quality. The project's objective was to gain additional understanding of the optimal ventilation configurations to minimize exposure to CO_2 or other contaminants.

KEY RESULTS: This study found that:

- At the same air exchange rate, the worst configuration (vents on same wall) had average CO_2 concentrations that were 52-77% higher than the best configuration (vents on opposite walls);
- The worst performing configurations also had more uneven distributions of CO_2, resulting in pockets of very high concentrations; and
- Using the better performing vent configuration could allow for a lower ventilation rate while maintaining good air quality and thus save energy.

BACKGROUND: In 2022, MKThink conducted a study to assess the concentration of CO_2 in classrooms under a variety of physical configurations and occupancies. This work, involving both field measurement and computational fluid dynamics (CFD) modeling was intended to identify whether methods could be developed to inform instructors about how to maintain high quality indoor air quality in real time. Results showed some interesting trends based on air exchange rate (AEC) and location of the exhaust vent compared to the location of the fresh air inlet vent, but the project stopped short of reaching defined conclusions that could be used to manage air quality while minimizing energy use. The major objective of this follow-on effort was to further analyze the results of the previous work to provide additional guidance in the placement of ventilation system and to identify possible methods to manage energy from HVAC while maintaining air quality.

PROJECT STATUS/RESULTS: MKThink conducted additional analysis for a subset of the original study including four inlet-exhaust location configurations and three different air exchange rates deemed to be within normal operating ranges of commercial HVAC systems. As expected, for the same vent configuration, the average CO_2 concentration tracked monotonically with the air-exchange rate, decreasing as the AEC (inlet clean air flow) was increased. CFD modeling of the various configurations also indicated that the average CO_2 concentration and the variability (difference from average) differed significantly with different inlet-exhaust configurations. Location of exhaust vents on the opposite wall from the primary air inlet showed significantly lower average values and less variability than configurations where the exhaust was on the same wall or a wall perpendicular to the inlet vent. Unfortunately, the CFD models assumed a higher human volumetric breathing rate than a more recent literature search indicates, making direct comparison of the CFD and previous measurement in the classroom difficult. This project is now completed.

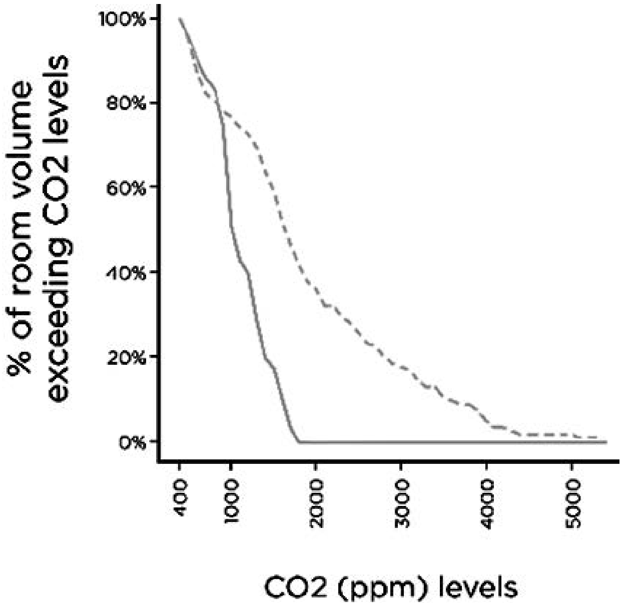

Figure 1. Percentage of the room volume exceeding CO_2 concentrations (ppm) for vents on the same wall (dotted line) vs vents on opposite walls (solid line).

Funding Source: Office of Naval Research

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Last Updated: November 2023

Appendix D: Grid Technology Development

D1: Coconut Island DC Microgrid

OBJECTIVE AND SIGNIFICANCE: HNEI has developed a DC-based microgrid test bed on Coconut Island (Figure 1), home to the University of Hawaiʻi's Hawaiʻi Institute of Marine Biology (HIMB). The project aims to demonstrate and assess the reliability, resilience, and energy efficiency benefits of a DC microgrid serving two HIMB buildings. It will compare the efficiency of serving lighting, cooling, plug loads, and EV charging with AC versus DC supplied power during normal operations. It will also 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: HIMB aims to serve as a model for sustainable systems, making it an ideal site for a microgrid test bed centered around renewable energy technology. This test bed will exemplify a remote area susceptible to energy disruptions while fulfilling critical power requirements. The project's key objectives encompass: 1) implementing innovative, efficient, and reliable clean energy technologies; 2) creating a research platform for studying resilient DC microgrid technologies in a tropical coastal environment; and 3) advancing solar DC-powered transportation solutions, both on land (e-cars) and at sea (e-boats).

HNEI's Grid System Technologies Advanced Research Team (Grid*START)* partnered with the Okinawa Institute of Science and Technology, Japan and PUES Corporation, Japan to develop a DC-powered e-car and e-boat (Figure 2), and portable emergency power source, all using swappable batteries. The e-mobility solutions are charged with solar energy from a 6.2 kW rooftop solar PV system coupled with an 8 kWh battery energy storage system (BESS). HNEI Grid*START* also collaborated with the University of Indonesia (UI). UI designed a new DC-DC converter (DCON) that 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 microgrid provides DC lighting, DC air conditioning, refrigeration, EV charging, and power for critical building loads, with minimal reliance on the grid during peak demand times.

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

PROJECT STATUS/RESULTS: The DC microgrid system located in a dedicated electrical room has been successfully installed and commissioned (Figure 3). This room houses numerous electrical components, including switches, breakers, controls, a BESS, DC-DC converters, and associated wiring. The 6.2 kW rooftop solar PV system and 8 kWh BESS have been seamlessly integrated for operation within the DC microgrid. With the system controller in place and properly programmed, the DC microgrid is now fully operational and undergoing performance testing across a range of scenarios, including resilient supply of energy to critical load centers in islanded mode.

HNEI Grid*START* is using the established microgrid infrastructure and operational data being collected as a pilot site to initiate extended microgrid research endeavors and associated new funding opportunities.

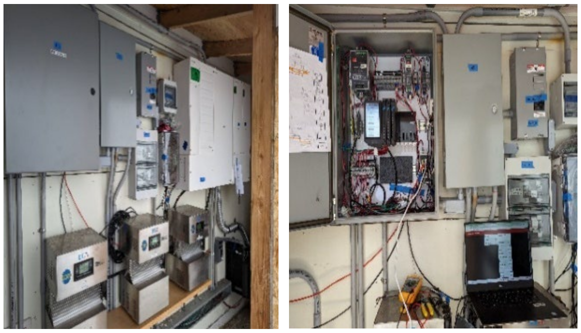

Figure 3. DC microgrid components in a dedicated electrical room (left) and system's controller box (right).

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

Hawai‘i Natural Energy Institute Research Highlights

Appendix D: Grid Technology Development

D2: Advanced Conservation Voltage Reduction Development and Demonstration

OBJECTIVE AND SIGNIFICANCE: HNEI Grid*START* is demonstrating conservation voltage reduction (CVR) as an effective way to conserve energy on a U.S. Marine Corps (USMC) base in Okinawa, Japan. CVR works by seamlessly lowering the operating voltage within the acceptable operating band on distribution circuits serving customer loads, which can reduce customer energy use and peak demand.

BACKGROUND: The primary value of CVR implementation is reduced energy use by more effectively managing customer service voltage. CVR is expected to reduce energy consumption by 0.7% to 0.9% for every 1% reduction in voltage (i.e., CVR factor). In close collaboration with USMC Facilities personnel in Okinawa, seven distribution service transformers on a branch of the 13.8 kV circuit serving the Plaza Housing complex were selected for a CVR field test.

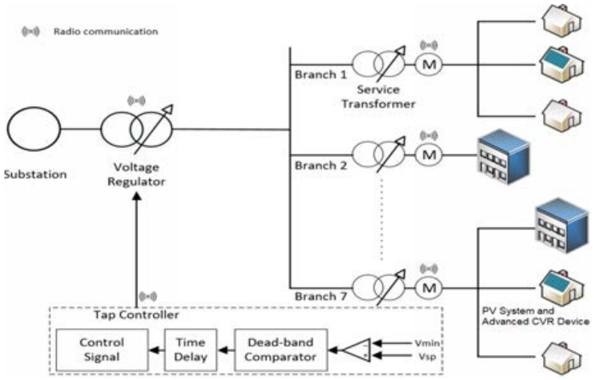

Figure 1. CVR demonstration system architecture.

To control the voltage at downstream service transformers, the CVR-controlled feeder section is isolated with a new voltage regulator (VR). The VR’s load tap changer (LTC) can shift the voltage profile of the entire feeder down, but it is unable to manage individual low- or high-voltage points along the feeder path. This means that the minimum voltage point along the feeder limits voltage reduction by the LTC. To achieve greater CVR benefits, HNEI has patented and field-demonstrated a method of localized voltage management with an advanced CVR device. This device uses local measurements from an existing AMI meter to: 1) smooth the voltage profile by managing and regulating the reactive power output of inverters; 2) increase voltage at the critical minimum voltage point regulated by the VR; and 3) provide maximum CVR benefits for all customers.

PROJECT STATUS/RESULTS: The VR and associated CVR controller, as well as the advanced CVR device, were successfully installed and commissioned in the field. Communication challenges were addressed to improve the controller’s performance and data collection capabilities. HNEI analyzed weekly measurement data from the USMC Camp Butler team to estimate the energy savings achieved by implementing CVR across the downstream transformers. The CVR assessment determined that the CVR factor for the feeder section serving the seven transformers ranges from 0.75% to 0.93%, translating to 1.82 to 2.26 MWh of energy savings per month.

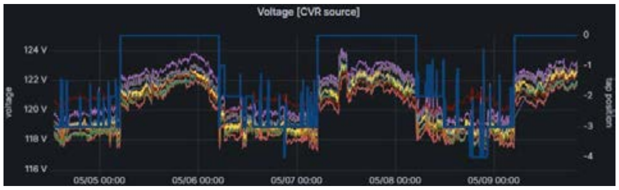

Figure 2. Voltage profiles with CVR on and off. The tap position (blue) at 0 indicates CVR is off.

During a typhoon, the VR was disconnected from the Plaza Housing distribution grid due to an apparent internal fault. Tests will be conducted to determine if the VR can be returned to service. If so, HNEI Grid*START* will continue collecting field data to further assess and evaluate the coordinated operation of the CVR controller, the VR, and the advanced CVR device at the low voltage point on the feeder. HNEI Grid*START* will also assess the CVR factor of the loads connected to each transformer to characterize the differential CVR benefits across alternative classes of end-use loads.

Figure 3. Voltage drop (red) is reduced when the advanced CVR controller is enabled and reactive power (blue) is dispatched.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

D3: Hawaiʻi Virtual Power Plant (Hi-VPP) Demonstration

OBJECTIVE AND SIGNIFICANCE: HNEI Grid*START* has developed the Hawaiʻi Virtual Power Plant Demonstration project (Hi-VPP). The project's primary goals are to: 1) assess the economic value and operational effectiveness of customer-sited battery and solar (BESS+PV) resources through demonstration and 2) evaluate the technology application and the value proposition, while prioritizing alternative use cases based on stakeholder interests and functional/economic trade-offs. These resources serve both the customer and the grid when aggregated as part of a virtual power plant (VPP).

This project is expected to provide key insights into the economic synergy, optimization of multiple services under BESS control, and the trade-offs between simple, low-bandwidth and advanced, highly coordinated methods of VPP aggregation. Ultimately, it will help in quantifying the business case for VPPs, including the value proposition for customer participation and utility utilization of the same.

BACKGROUND: Upon the successful conclusion of the JUMPSmart Maui (JSM) smart grid project funded by the New Energy and Industrial Technology Development Organization (NEDO) of Japan, HNEI negotiated an Equipment Transfer Agreement, through which HNEI acquired from NEDO significant grid assets deployed in the JSM project. HNEI Grid*START* capitalized on this acquisition by utilizing the Sunverge Solar Integration System (SIS) BESS+PV units located at Haleakala Solar's business office to conduct this VPP project.

Figure 1. Sunverge SIS BESS + PV units on Maui.

PROJECT STATUS/RESULTS: HNEI Grid*START* has designed control algorithms that integrate with building load forecasts and PV rooftop power generation forecasts. This integration optimizes the charge/discharge schedule of BESS units, effectively reducing electricity costs while ensuring power requirements are met during utility issued demand response events (Figure 2).

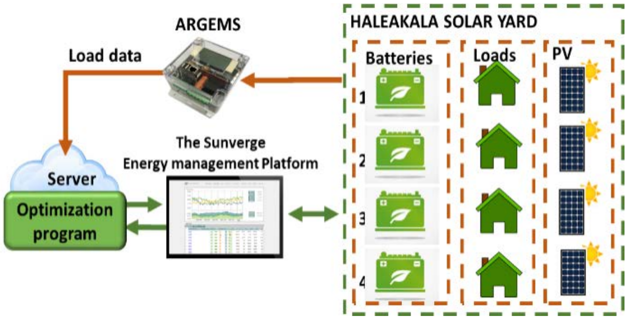

Figure 2. System overview of the project.

HNEI Grid*START* is utilizing the data collected to develop a methodology to assess the potential benefits of customer participation in demand response programs offered by the Hawaiian Electric Company. This evaluation aims to determine the optimal VPP participation capacity, which in return could minimize customers' total electricity bills.

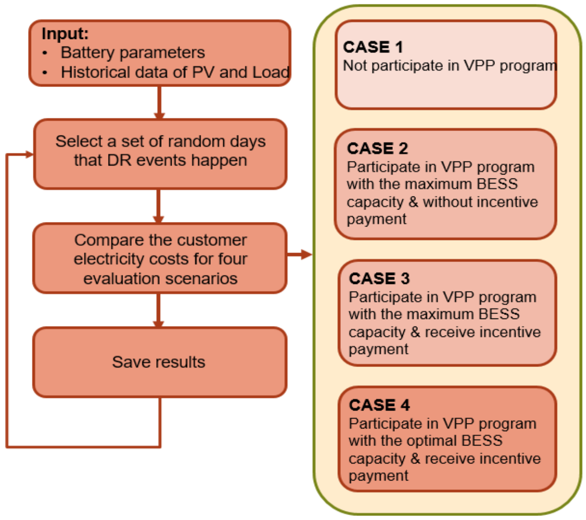

Figure 3. Evaluation process and case studies.

Through these demonstrations, HNEI Grid*START* aims to test and evaluate the system's performance and functionality, thereby acquiring valuable insights and information for further analysis and decision-making. HNEI is currently in the process of preparing a conference proceeding paper that summarizes our research findings to date.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix D: Grid Technology Development

D4: Assessing Dynamic Response of Converter-Dominated Power Systems

OBJECTIVE AND SIGNIFICANCE: This project aims to develop local expertise in developing and validating modeling and control solutions for today's power grid, which is increasingly integrating inverter-based resources (IBR). The overarching technical goal is to identify the type and detail of converter models required to accurately represent power system dynamical phenomena across multiple time scales for converter-dominated power systems (CDPS). The Hawaiʻi power grid serves as an exceptional testbed for investigating the complex dynamics and transitional states between CDPS and the broader power grid. This positions the project as critically important for Hawaiʻi, as it is poised to drive significant progress in these areas. The initiative strategically targets these complexities to enhance the stability, efficiency, and resilience of Hawaiʻi's power infrastructure, ensuring its readiness for the evolving demands of a sustainable energy future.

BACKGROUND: HNEI previously collaborated with the Natural Energy Laboratory of Hawaiʻi Authority (NELHA) on their microgrid analysis project, which evaluated microgrid options for NELHA's Hawaiʻi Ocean Science and Technology (HOST) Park. The HOST Park features the world's most extensive seawater distribution system, which relies heavily on converter-based generation and complex loads, including significant variable frequency drives (VFDs), photovoltaic (PV) arrays, and a hydrogen production facility equipped with a converter-driven electrolyzer (198 kW) and mobile storage of up to 300 kg of compressed hydrogen. These features make the HOST Park an ideal example of a CDPS integrated with the larger grid. NELHA agreed to collaborate with HNEI to use the HOST Park's power system as the case study for this project. Key project tasks include: 1) installing new power quality meters and data collection, 2) generating, calibrating, and validating baseline models, and 3) using the models to study salient dynamics of converter-based generation and loads within the HOST Park power system.

PROJECT STATUS/RESULTS: HNEI, working closely with NELHA, developed a detailed single-line diagram of the HOST Park research campus microgrid (Figure 1). This allowed HNEI researchers to identify various distribution systems components, such as transformer sizes and their set-up, and VFD load information for water pumps and PV system components such as inverters and panels. Following this effort, HNEI pinpointed three critical locations and successfully deployed power quality meters on them, along with all necessary data acquisition components.

Figure 1. Overview of the NELHA HOST Park's electrical load sections (schematic on Google Earth overlay).

Figure 2 shows the deployed equipment and the structure for data transfer, as well as the utilized software for data recording and analysis. A draft model of the NELHA research campus microgrid has been created in PowerFactory. Currently, HNEI is utilizing the gathered data to calibrate and fine-tune the model.

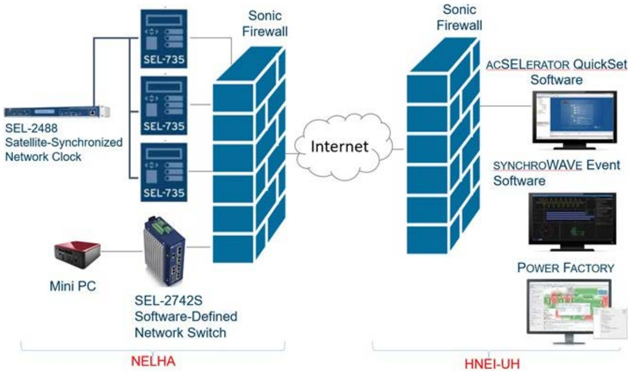

Figure 2. Overview of all installed equipment with data transfer infrastructure and associated software utilized for the project.

Funding Source: Department of Energy

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Last Updated: November 2023

Hawai‘i Natural Energy Institute Research Highlights

Appendix D: Grid Technology Development

D5: Bidirectional EV Charging Demonstration Project

OBJECTIVE AND SIGNIFICANCE: The main objective of this project is to develop, evaluate, and demonstrate the performance of novel algorithms to optimize the charge/discharge of shared fleet vehicles for energy cost minimization. Project experience and results will not only advance energy research but also 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 Grid*START* is collaborating with IKS Co., Ltd. (IKS) on technology development, testing, and demonstration of advanced control of two bidirectional electric vehicle (EV) chargers ("H-PCS") on the campus of the University of Hawai‘i at Mānoa (UH). The two designated parking stalls, indicated by the red rectangle, are located adjacent to the Bachman Annex 6 building indicated by the orange rectangle (Figure 1). The H-PCS was developed by IKS with support from Hitachi Limited as part of the earlier JUMPSmart Maui smart grid demonstration project, where Grid*START* was one of the partners.

Figure 1. Location of bidirectional EV chargers.

Two EVs procured by the project for this research are currently used by designated university personnel in a car-sharing system accessed via a secure web-based car scheduling application developed by HNEI Grid*START*.

The novel H-PCS control algorithms developed by HNEI Grid*START* first ensures that the shared vehicles for UH personnel use are efficiently assigned and readily available for transport needs. Simultaneously, the autonomous controls 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. The autonomous controls may also support the operational needs of the local utility operator (Hawaiian Electric Company) through the supply of grid ancillary services in return for financial compensation.

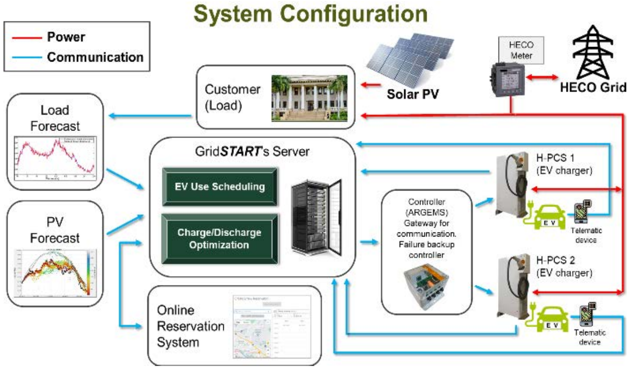

Figure 2. Functional system diagram.

HNEI Grid*START*'s novel algorithms also incorporate data fed from state-of-the-art in-house developed forecasts of campus building demand and on-campus solar PV power production. This allows the system to maximize 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: The project was field operationalized in July 2023, with research focus now on analyzing system performance data and exploring enhancements of the integrated autonomous control algorithms hosted on the project's dedicated server. The system's energy cost minimization benefit is being assessed across a range of alternative building load and PV profile cases, EV use patterns, charging modes, and utility tariff structures to explore system scale up. A vehicle telematic system was successfully installed to capture real-time car use data while on the road including EV battery state of charge, vehicle location, and energy consumption. Data from the telematic system is planned for enhancement of predictive algorithms – enabling more informed projections of EV use patterns to improve the scheduling of EV charge and discharge controls.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

D6: EV Charging Infrastructure Master Plan for USMC Camp Fuji, Japan

OBJECTIVE AND SIGNIFICANCE: Aligned with the ambitious climate goals outlined in United States Executive Order 14057, the United States Marine Corps (USMC) has partnered with HNEI Grid*START* to develop a comprehensive master plan for fleet electrification and electric vehicle (EV) infrastructure implementation at Combined Arms Training Center (CATC) Camp Fuji in Gotemba, Japan. This plan will establish an accessible network of EV charging stations that are efficient, convenient, and safe, with the aim of encouraging EV adoption and promoting sustainability at CATC Camp Fuji.

Figure 1. View of Mt. Fuji from within CATC Camp Fuji (Source: U.S. Indo-Pacific Command).

BACKGROUND: CATC Camp Fuji, situated at the base of Mt. Fuji in Gotemba, Japan, is a USMC installation and training area encompassing various facilities such as barracks, warehouses, repair shops, fleet garages, and a military police post. Following the directives outlined in Executive Order 14057, the Camp is planning to transition its non-tactical vehicle fleet to EVs in the coming years. Presently, public EV charging infrastructure in Japan is limited. Therefore, Camp Fuji’s EV charging network must be thoughtfully designed to accommodate the specific usage needs of each fleet vehicle, while also incentivizing the adoption of privately owned EVs at the camp.

PROJECT STATUS/RESULTS: In August 2023, HNEI Grid*START* met with stakeholders at CATC Camp Fuji to devise a fleet electrification strategy and identify optimal locations for EV charger deployment to serve the Camp’s needs. This strategy delineated the vehicles most suitable for prompt conversion to EVs, as well as those better suited for conversion as public EV infrastructure and technology evolve. Considerations within the electrification strategy included range requirements, emergency responsibilities, charging turnaround times, and the current state of EV technology and infrastructure. The meeting also identified key priority locations for the installation of EV charging facilities. These selections considered existing infrastructure, current parking trends, geographical limitations, and the encouragement of EV ownership among Camp personnel. At these chosen locations, an optimized combination of DC Fast Chargers and Level 2 chargers was determined based on vehicle types and their expected usage demands.

Figure 2. Example of EV charging location from the master design file.

As part of the master plan, HNEI Grid*START* is presently evaluating the capacity of Camp Fuji’s existing electrical infrastructure to accommodate the proposed EV chargers. With the cooperation of Camp Fuji personnel, HNEI is leveraging historical AMI data for CATC Camp Fuji to evaluate if the existing conductors, transformers, and panels can handle the additional load associated with EV chargers. The analysis will provide an assessment of the infrastructure’s current capacity, while also identifying load patterns linked to seasons, population changes, or training activities.

Concurrent with the AMI data analysis, HNEI is developing a master planning file that will encompass the proposed construction drawings for each selected EV charging infrastructure site. Upon completion, these plans will be used as a technical blueprint for estimating the potential costs of fleet electrification infrastructure additions at each location and as a tool for visualizing the phases of EV infrastructure integration at Camp Fuji.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

D7: Advanced Power System Laboratory (APSL)

OBJECTIVE AND SIGNIFICANCE: HNEI Grid*START* has designed and equipped its new Advanced Power System Laboratory (APSL) to conduct research, development, test, and evaluation (RDT&E) in support of power systems modernization and renewable energy integration. The APSL has a highly flexible architecture and is the first laboratory of its kind in Hawaiʻi – able to test AC and DC devices, systems, and microgrids within a managed field representative electrical environment. The lab will significantly enhance HNEI's ongoing research endeavors by providing a state-of-the-art test environment that extends its RDT&E capabilities to deliver next-generation smart grid technologies.

BACKGROUND: The APSL comprises of significant components, including three AC/DC equipment test bays and a 35 kW rooftop PV system connected to four advanced PV inverters with grid support functions (Figure 1). This PV system serves a dual purpose, supporting the lab's research needs and assisting the University of Hawaiʻi in achieving its net zero energy consumption goal. Additionally, the lab hosts a real-time grid simulator connected to a 30 kVA power amplifier, facilitating power hardware-in-the-loop (HIL) testing. The power HIL system enables researchers to evaluate electrical power equipment as a unit under test (UUT) in a real-time simulated grid environment.

The three modular AC/DC test bays (see Figure 2) have been designated for evaluating advanced functions, communications and controls of various UUT. These include advanced PV inverters, EV chargers those with vehicle-to-grid (V2G) and vehicle-to-home (V2H) bidirectional power flow capabilities, battery energy storage systems (BESS), power monitoring and edge computing devices, AC or DC loads/appliances and load control devices, and voltage management equipment, among other innovative technological solutions.

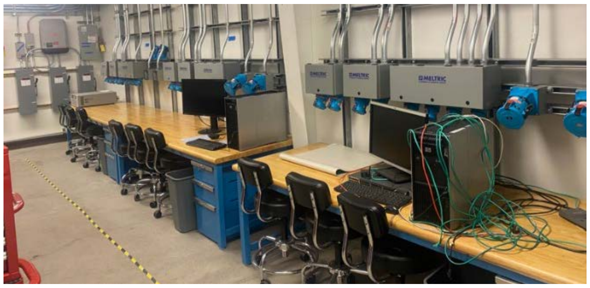

Figure 2. Three AC/DC equipment test bays.

PROJECT STATUS/RESULTS: The design, permitting, and construction of the electrical infrastructure of the APSL are now complete, rendering the lab available for use. In addition, there is an ongoing procurement process for a microgrid control system that encompasses integrated microgrid modeling tools and the capability to seamlessly integrate with the APSL's existing power HIL system. This integrated system will empower HNEI to introduce a comprehensive microgrid design and control training curriculum aimed at power system engineers across the Asia-Pacific region. Furthermore, the APSL and its power HIL equipment will be employed in tandem with HNEI Grid*START*'s field-deployed microgrid testbed on Coconut Island for the development and testing of new, resilient microgrid control algorithms. These algorithms will address dynamic load management, facilitated by a recently secured U.S. DOE-sponsored research grant of approximately $1 million.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

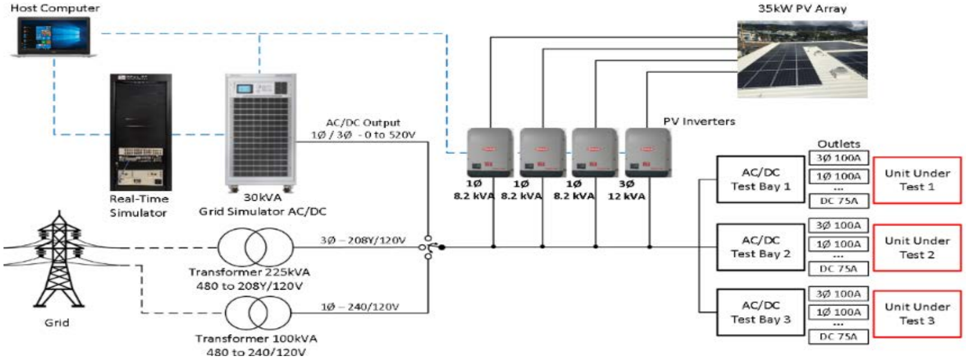

Figure 1. HNEI Grid*START*'s Advanced Power System Lab architecture.

E1: Sustainable Aviation Fuel Production

O<u>BJECTIVE AND</u> S<u>IGNIFICANCE</u>: 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 9th 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.

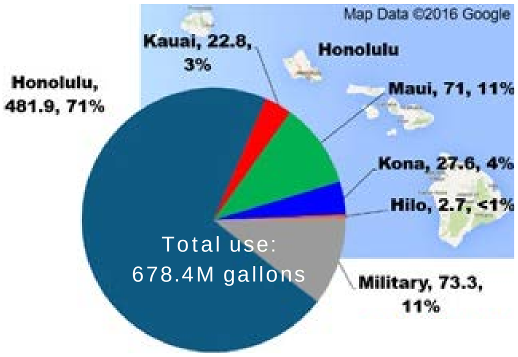

Figure 1. Commercial and military jet fuel use in 2015.

P<u>ROJECT</u> S<u>TATUS</u>/R<u>ESULTS</u>: 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.

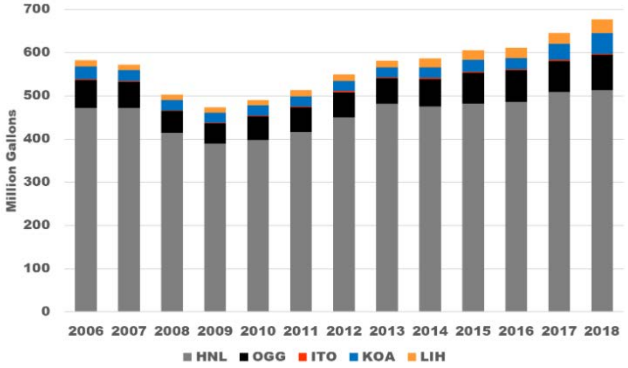

Figure 2. Commercial jet fuel consumption in Hawaiʻi.

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 were summarized and published in **Construction and Demolition Waste-Derived Feedstock: Fuel Characterization of a Potential Resource for Sustainable Aviation Fuels Production** in the *Frontiers in Energy Research* journal.

As shown in Figure 3, 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.

Tests of clean wood fuel from the invasive species (Leuceana spp., common name koa haole) and CDW material were conducted at a commercial gasification technology provider facility to evaluate product composition and yields and identify contaminants

(Figure 4). Test reports for koa haole ("***Gasification of Leucaena leucocephala Stemwood***") and CDW ("***Gasification of Synthetic CDW 1***"), respectively, are available on HNEI's website. The test results detail the reactor operating conditions, fuel characteristics, concentrations of major permanent gas species (H_2, CO, CH_4, CO_2), and concentrations of inorganic species present as contaminants in the product gas stream (H_2S, NH_3, HCl, As, Cd, Cr, Pb, Mg, P, K, Se, Na, Z, Hg). The increases of As, Pb, and Cr concentrations in the CDW product gas compared to clean wood product gas were notable, in the case of arsenic increasing from ~1 part per billion (ppb) to ~200 ppb. The data indicate that managing the gas quality through feedstock treatment/blending or product gas cleanup will be required.

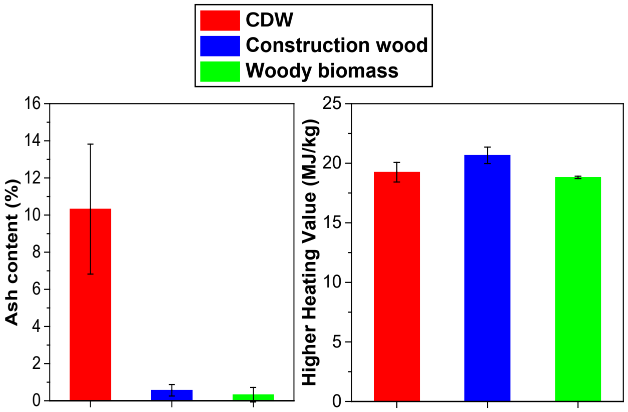

Figure 3. Ash content (left) and heating value (right) of the combustible fraction of CDW compared to construction wood and woody biomass.

Utilizing urban waste resources as feedstock for SAF production has the advantages of both reducing amounts of material entering the limited landfill space and reducing dependence on imported energy. A statewide assessment of urban waste resources currently entering landfills is summarized in Table 1 below[3]. Waste amounts generally scale according to population, with Honolulu having the largest total despite the use of waste for fuel in the HPOWER power plant. Integrating solid waste management and fuel production with a view of treating the state as a single management unit rather than four individual county units could be a beneficial approach to meet waste management, energy resiliency, and greenhouse gas abatement goals. Analysis of this integrated approach will be conducted in the coming year.

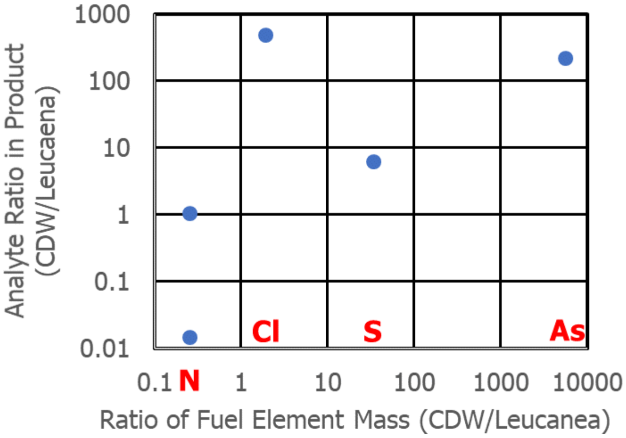

Figure 4. Relative ratios of elements in present in fuels to ratios in the product gas stream.

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 and partners;
- Continued stakeholder engagement;

Table 1. Summary of combustible waste materials currently entering landfills (tons per year).

County	**Maui**	**Kaua'i**	**Hawai'i**	**Honolulu**	**Total**
Non-food biomass	111,151	43,279	120,346	22,207	296,983
Plastics and textiles	40,832	13,904	27,616	6,440	88,792
CDW	-	-	-	208,000	208,000
Urban Total	151,983	57,183	147,962	236,647	593,775

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[3] Adapted from Turn, S.Q., R.B. Williams, and W.Y. Chan. 2022. Resources for renewable natural gas production: A Hawai'i case study. *Environmental Progress & Sustainable Energy*. e14002. https://doi.org/10.1002/ep.14002.

- 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[4]. 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. This work was summarized and published in **Review of Biomass Resources and Conversion Technologies for Alternative Jet Fuel Production in Hawai‘i and Tropical Regions** in the *Energy and Fuels* journal.

The EcoCrop model was used to complete an assessment of plant production requirements to agro-ecological attributes of agricultural lands in the State. Land use constraints included agricultural zoning, land capability classes (an indicator of soil quality), slope, service by irrigation systems, and current agricultural activities. 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 (Figure 6).
The EcoCrop model provides an estimate of each energy crops' productivity across the agricultural landscape. Aggregated yield of biobased feedstock and conversion efficiency from feedstock to final energy product were used as the basis for SAF technical potential estimates under four scenarios:

- Scenario 1 - agricultural zoning, slope less than 20%, land capability class 1 to 6
- Scenario 2 - agricultural zoning, slope less than 20%, land capability class 1 to 6, excluding land serviced by irrigation systems,
- Scenario 3 - agricultural zoning, slope less than 20%, land capability class 1 to 6, excluding land serviced by irrigation systems and land currently in agricultural use, and
- Scenario 4 - agricultural zoning, slope less than 20%, land capability class 1 to 6, excluding land serviced by irrigation systems and land currently in agricultural use other than pasture.

All scenarios assume a EcoCrop suitability index >0.5 on a scale of 0 to 1 using rainfed conditions.

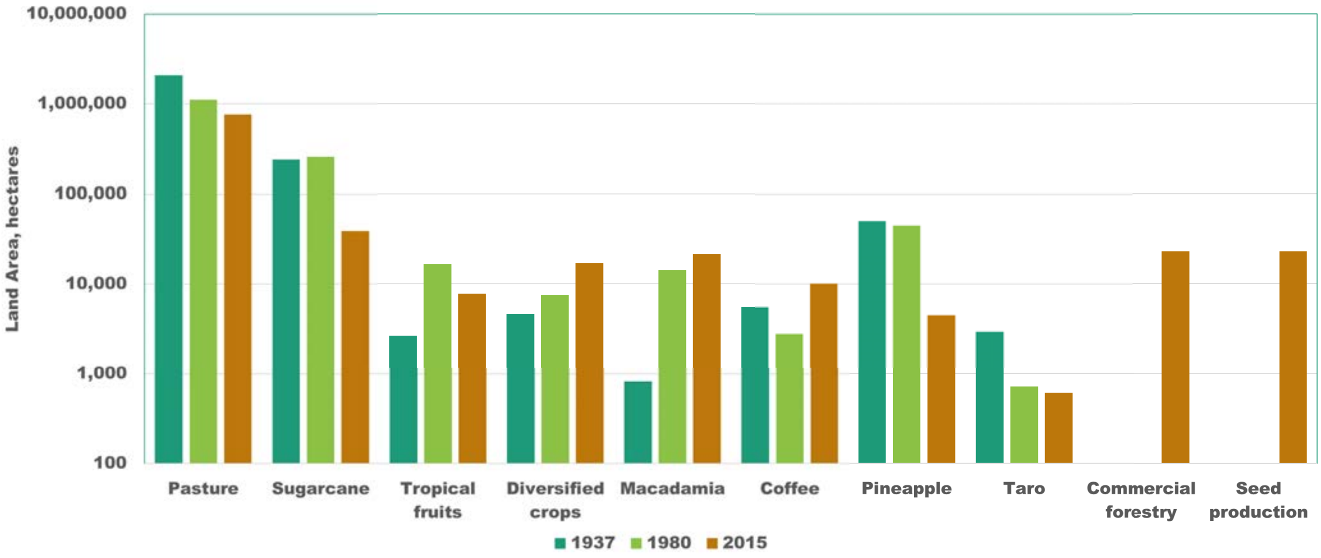

Figure 5. Breakdown of agricultural land use in Hawai‘i; in 2015, approximately 100,000 acres were harvested.

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[4] Adapted from data in Melrose, J., R. Perroy, S. Cares. 2015. *Statewide agricultural land use baseline 2015*. Prepared for the Hawai‘i Department of Agriculture. Honolulu, Hawai‘i.

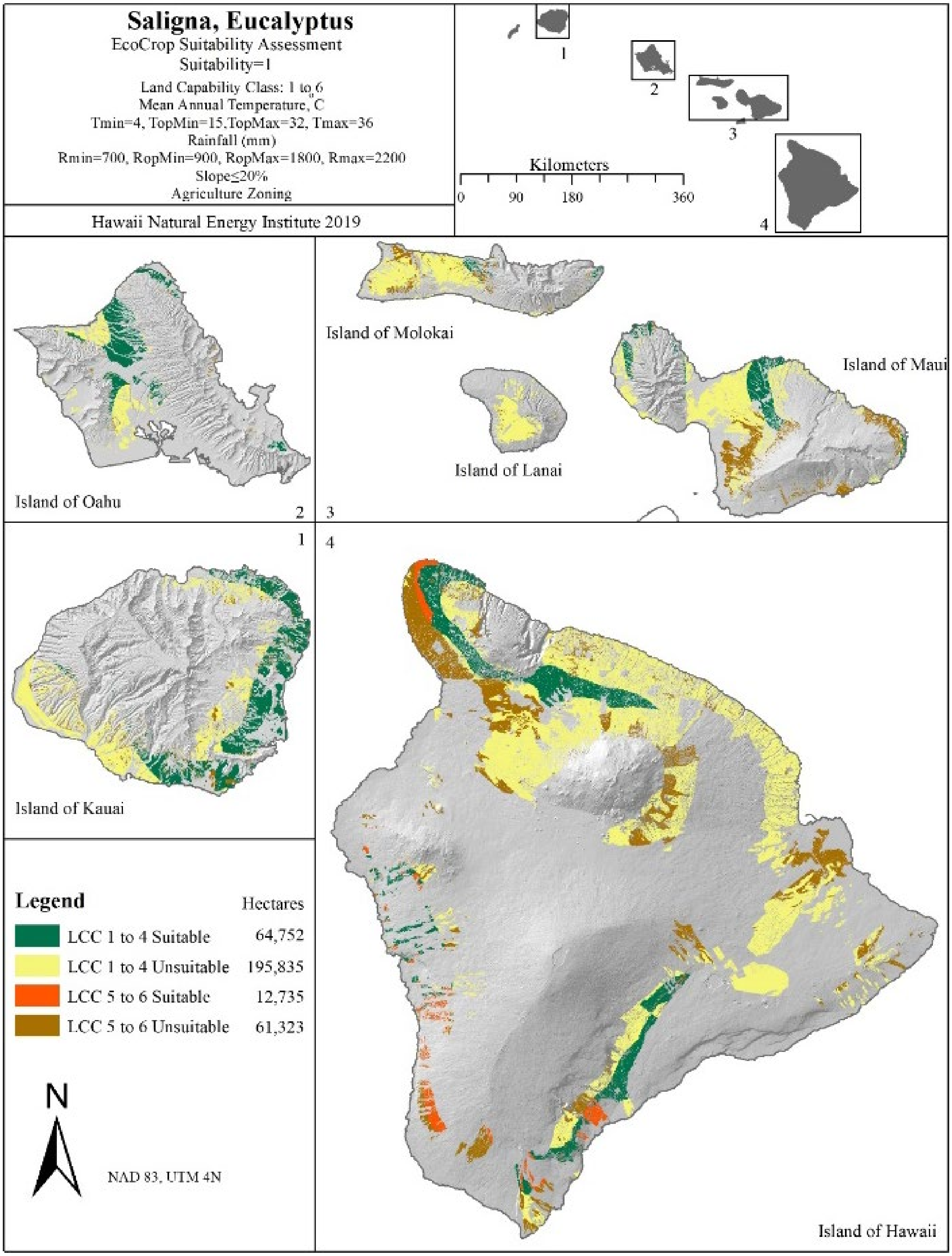

Figure 6. EcoCrop assessment of Saligna, Eucalyptus.

Results of the analyses are shown in Figure 7. Note that the results are not mutually exclusive, i.e. the same land area may be included in the estimates of multiple crops. Scenario 1 includes the greatest land area and this is reflected in highest annual SAF production potential estimates, of up to ~100 million gallons. Scenario 2 removes any land service by an irrigation system from the analyses, resulting in a reduction in potential to a ~80 million gallons. Scenario 3 further restricts available lands by excluding those under production identified in a study conducted by the University of Hawai‘i at Hilo (UH Hilo) for the Hawai‘i Department of Agriculture[5], resulting in SAF production potential estimates <40 million gallons per year. Scenario 4 considers the dual use of land to support energy crops and pasture by including pasture lands identified in the UH Hilo Baseline report. This results in maximum estimates of ~70 million gallons per year. A report detailing these results is currently being drafted.

Pongamia production logistics

EcoCrop energy crop modeling identified pongamia as having the greatest oil production potential based on suitable growing area and yield. The geographic distribution of suitable growing areas across the state provides an opportunity to select pongamia primary processing sites that minimize transportation costs. Seeds in their pods would be harvested and transported to a primary processing location where the seed and pod could be separated, oil could be extracted from the seed, and oil and de-oiled seed

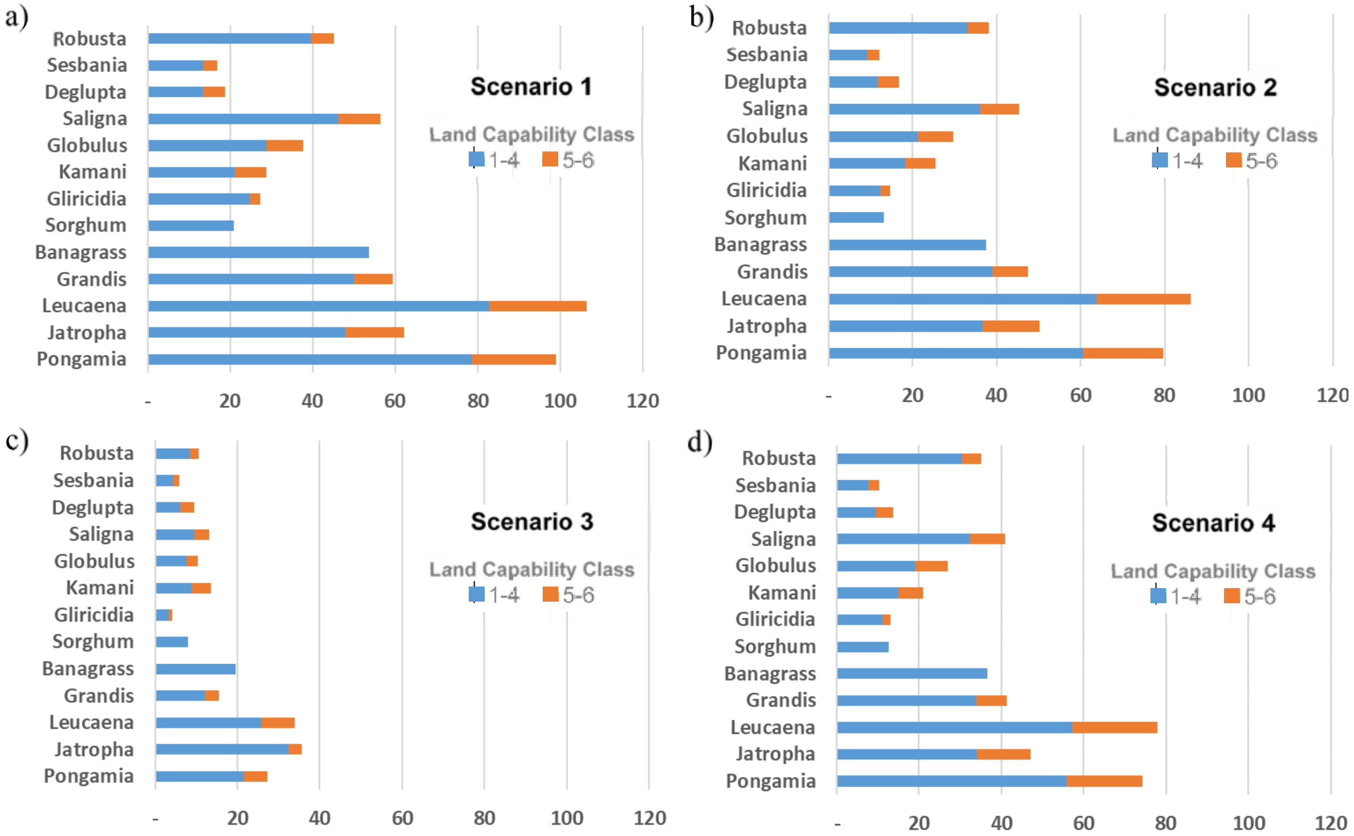

Figure 7. SAF potential (million gallons per year) for 13 energy crop feedstocks under four scenarios: (a) agricultural zoning, slope less than 20%, (b) agricultural zoning, slope less than 20%, exluding land serviced by irrigation systems, (c) agricultural zoning, slope less than 20%, exluding land serviced by irrigation systems and land currently in agricultural use, and (d) agricultural zoning, slope less than 20%, exluding land serviced by irrigation systems and land currently in agricultural use other than pasture. All scenarios assume a EcoCrop suitability index >0.5 on a scale of 0 to 1 using rainfed conditions.

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[5] Melrose, J., R. Perroy, S. Cares. 2015. *Statewide agricultural land use baseline 2015*. Prepared for the Hawai‘i Department of Agriculture. Honolulu, Hawai‘i.

cake could be upgraded. Land zoned for industrial use (brownfield site) on each island was considered as potential primary processing sites. Greenfield sites were also considered – identified as land zoned for agriculture with slope less than 5%, and a minimum contigous area of 125 acres. This would accomodate space needed for processing, storage, and possible colocation of complementary industries utilizing the de-oiled seedcake and pod to develop coproducts. A tonne-kilometer value, Tkm_i, was calculated for all i candidate processing location using equation (1).

$$Tkm_i = \sum_{j=1}^{n} m_j \cdot d_j \qquad (1)$$

Where m_j is the mass of seed pod harvested at a production location j, d_j is the distance traveled over the existing road network between production location j to the processing site i, and n is the number of pongamia production locations. Production locations were based on analysis using a 1 km x 1 km grid. A relative index, C_{ik}, shown in equation (2), was used to compare Tkm values across islands.

$$C_{ik} = \left(\frac{Tkm_i - Tkm_{min}}{Tkm_{max} - Tkm_{min}}\right)_k \quad (2)$$

where Tkm_{min} and Tkm_{max} are the minimum and maximum Tkm values, respectively, for island k. Candidate sites for Scenario 1, ranked from lowest (C_{ik}=0) to highest (C_{ik}=1) value, are shown in Figures 8 and 9 for brownfield and greenfield locations, respectively.

Greenfield site options are more numerous than brownfield locations and may afford reductions in transportation requirements as shown in the figures. Brownfield sites are anticipated to offer access to pre-existing utilities that could reduce costs of developing the processing facilities. The locations for minimum cost sites depend on the production scenarios for pongamia. Pongamia production system planning would require verification of industrial zoning, farmer acceptance of pongamia production, community acceptance, and economic viability of all value chain participants. Continued system evaluation is planned moving forward.

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.

Invaseness Assessment

Pongamia (*Millettia pinnata*) (Figure 10) is a tree, native to the tropics, that bears an oil seed and has plantings established on Oʻahu. Under this project, an observational field assessment of trees in seven locations on Oʻahu 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 Oʻahu. 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 Oʻahu, 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. A detailed technical report titled "***Observational Field Assessment of Invasiveness of Pongamia (Millettia pinnata), A Candidate Biofuel Crop in Hawaiʻi***" summarized this work and is available on HNEI's website.

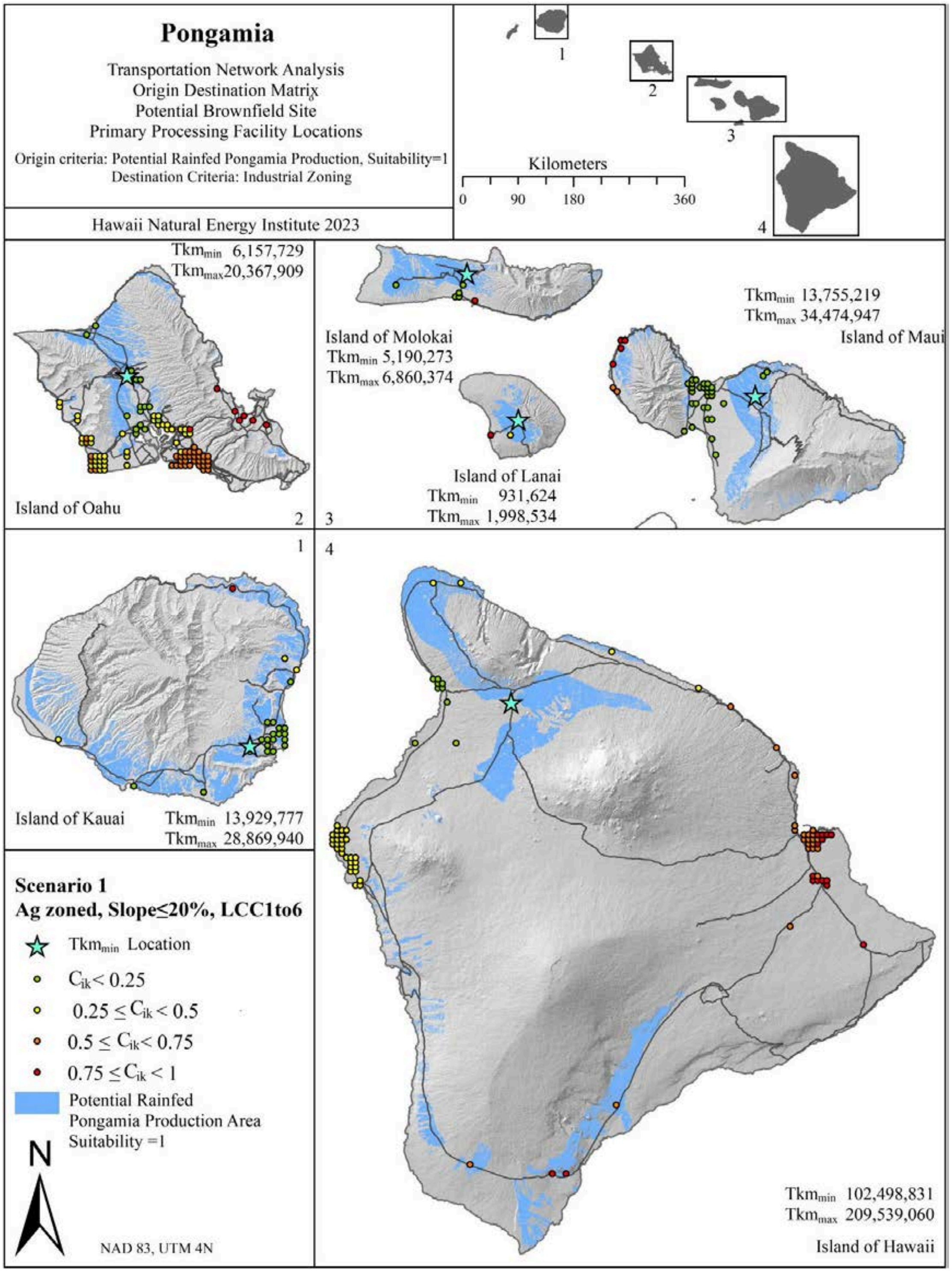

Figure 8. Results of analysis to identify locations to minimize transportation costs of harvested pongamia seed pods to a central brownfield processing site. Blue areas are zoned for agriculture, have slope less than 20%, have land capability class ratings of 1 through 6, and have EcoCrop suitability values of 1.0 for pongamia under rainfed conditions. Potential brownfield processing locations, shown as colored circles, are zoned for industrial use. The star on each island identifies the location of Tkm_{min} corresponding to $C_{ik} = 0$.

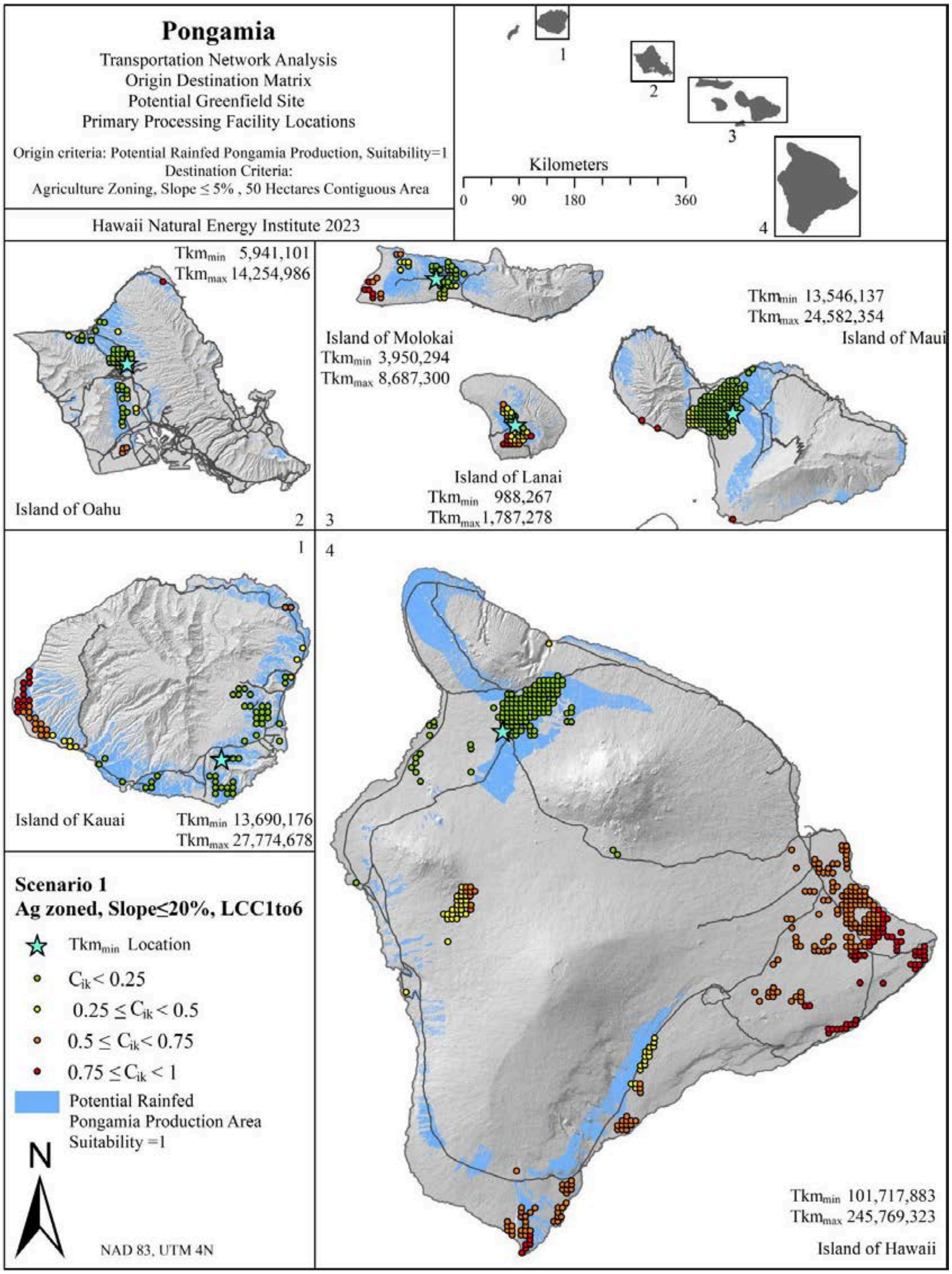

Figure 9. Results of analysis to identify locations to minimize transportation costs of harvested pongamia seed pods to a central greenfield processing site. Blue areas are zoned for agriculture, have slope less than 20%, have land capability class ratings of 1 through 6, and have EcoCrop suitability values of 1.0 for pongamia under rainfed conditions. Potential greenfield processing locations, shown as colored circles, are zoned for agriculture, have slopes ≤5%, and have 125 acres (50 hectares) of contiguous area. The star on each island identifies the location of Tkm_{min} corresponding to $C_{ik} = 0$.

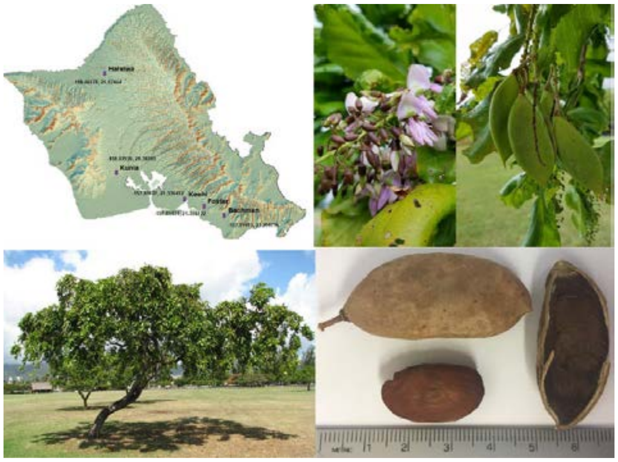

Figure 10. Locations and images of Pongamia.

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 (Figure 11). 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. These results were published in **Fuel Properties of Pongamia (*Millettia pinnata*) Seeds and Pods Grown in Hawai‘i** in the *ACS Omega* journal.

Figure 11. 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 (Figure 12). 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.

Pongamia pod leaching processes and pod torrefaction processes were summarized and published in **Water leaching for improving fuel properties of pongamia Pod: Informing process design** and **Upgraded pongamia pod via** torrefaction for the production of bioenergy, both in the *Fuel* journal, respectively.

Figure 12. Laboratory scale leaching and torrefaction test equipment.

Other Feedstocks

Other potential feedstocks for Hawai‘i, kukui (*Aleurites moluccanus*) and kamani (*Calophyllum inophyllum*) nut oils, were also explored. 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). The results of the study conducted on kukui were published in **Comprehensive Characterization of Kukui Nuts as Feedstock for Energy Production in Hawai‘i** in the *ACS Omega* journal.

Summary of SAF Production Potential Estimates

Table 2 compares the SAF technical production potential from urban wastes, oil seeds, grasses, and trees by island with 2018 petroleum jet fuel use data for the state. The use of SAF is currently limited to ≤50% blends with petroleum jet fuel. SAF production potentials from urban wastes range from 1 to 12% of 2018 petroleum jet fuel use by island. Energy crop production potentials range from 0.5 to 108.8% of 2018 petroleum jet fuel use by island. The largest mismatch for urban waste and energy crop potentials occurs in Honolulu, which has the highest jet fuel consumption. The energy crop SAF production potentials are more closely aligned to current petroleum jet fuel consumption on the outer islands under the most optimistic production scenario (see Figure 7a). We would like to note that totals in Table 2 do not include production on Moloka‘i and Lāna‘i.

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

Contact: Scott Turn, sturn@hawaii.edu

Last Updated: November 2023

Table 2. Summary of 2018 jet fuel use by island and technical production potentials from urban resources and energy crops (all values in million gallons per year, numbers in parentheses are % of 2018 island fuel use).

	Maui	**Kaua‘i**	**Hawai‘i**	**Honolulu**	**Total**
Fuel Burn 2018	81	33	50	513	677
Sustainable Aviation Fuel Technical Potentials					
Urban Waste	6 (7.3)	2 (6.7)	6 (11.5)	9 (1.8)	23 (3.4)
Energy Crop, Scenario 1, Suitability >0.5, Not Mutually Exclusive					
Oil Seed	14 (17.7)	13 (40.0)	50 (100.7)	9 (1.7)	86 (12.8)
Trees	16 (19.8)	15 (44.6)	54 (108.8)	9 (1.7)	94 (13.9)
Grasses	8 (9.7)	15 (45.2)	28 (56.1)	3 (0.5)	53 (7.9)

E2: Investigation of Waste-Based Feedstocks for Sustainable Aviation Fuel Production

OBJECTIVE AND SIGNIFICANCE: The aviation industry (civilian and military) faces significant challenges due to dependence on petroleum jet fuels and limited opportunity for electrification. Sustainable aviation fuels (SAF) from renewable resources provide alternatives to petroleum fuels and have added environmental benefits.

This research investigates the behavior of urban solid waste under possible gasification environments defined by temperature, pressure, and reactive environment. Results of this project can be used to inform participants in the urban solid waste to sustainable aviation fuel value chain, fuel suppliers, technology providers, gasification system operators, and research and development funding agencies. Project success will support the production, adoption, and use of sustainable bio-based aviation fuel – a much needed alternative to petroleum legacy fuels.

BACKGROUND: Feedstocks for SAF production include fiber, sugar, starch, and oil available from the forestry and agricultural sectors, and from urban solid wastes (USW). The fiber fraction of USW can be used to feed any of the downstream technology pathways leading to SAF products. EPA data shows that more than 100 million tons of combustible material are landfilled in the U.S. annually[6]. An estimation also reported that ~8.5 billion tons of waste materials could be mined from the existing U.S. landfills[7].

Although the use of USW for SAF feedstock shows high potential, it is not without challenges. USW may include municipal solid waste (MSW) and construction and demolition waste (CDW) that are heterogeneous in composition. A recent sampling program at a CDW landfill in Nānākuli, Hawaiʻi showed that CDW samples may contain ash approaching 10 wt% of fuel and ~25 elements of interest. In comparison, the ash in clean wood accounts for less than 1 wt% of fuel and contains ~12 elements of interest.

Gasification and gas cleanup of urban solid waste can be modeled as a series of thermochemical and phase equilibria steps defined by the thermodynamic state points of unit operations. Results can identify opportunities to improve gasification system performance by 1) managing urban solid waste components entering the gasification process, 2) guiding selection of reactor materials, and 3) avoiding operating conditions that result in ash deformation or pollutant formation. Under gasification conditions, ash present in the fuel may deform to produce vapors or liquid slags. The latter causes operating difficulties in the reactor, agglomerating bed material, and reducing fluid bed performance. The former may deposit on heat exchange surfaces, deactivate downstream catalysts, or contribute to pollutant formation. Understanding the behavior of ash elements under gasification conditions can provide information to further reactor design, process optimization, and strategies to mitigate the negative impacts of ash elements.

PROJECT STATUS/RESULTS: A literature review was conducted to identify the typical ranges for the elemental compositions of available waste-based fuels.

A sampling and characterization campaign determined the detailed composition of CDW materials mined from the PVT Land Company landfill over a period of time[8]. These data were used as input to FactSage for thermochemical equilibrium calculations to investigate:

- The fate of ash from CDW fuels under gasification at different temperatures, pressures, and in different reactive environments (oxygen, steam, and oxygen-steam);
- Possible interaction between ash elements and common fluidized bed materials or oxygen carriers in chemical looping systems;
- Possible interaction and/or deactivation of ash element and common catalysts; and

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[6] EPA. (2022) National overview: Facts and figures on materials, wastes and recycling. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials.

[7] Powell, J.T., J.C. Pons, and M. Chertow (2016) Waste Informatics: Establishing characteristics of contemporary U.S. landfill quantities and practices. *Environmental Science & Technology* 50, pp 10877-10884.

[8] Bach Q-V, Fu J, and Turn S (2021) Construction and Demolition Waste-Derived Feedstock: Fuel Characterization of a Potential Resource for Sustainable Aviation Fuels Production. *Frontiers in Energy Research* 9:711808.

- Strategies to control and/or remove gas phase inorganic species (e.g. As) from product gas using sorbents.

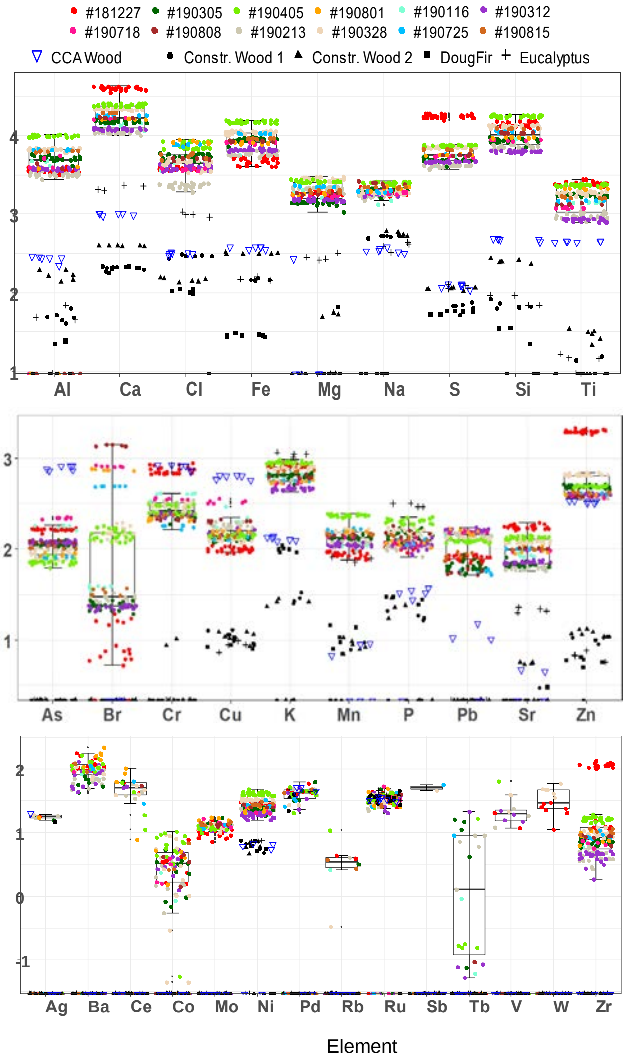

Figure 1. Element concentrations (log10 of ppm) in 12 CDW samples and five reference material samples.

The project was completed in 2023 and the significant findings and outcomes include:

- Establishing a database for fuel properties of waste-based feedstock.
- The available data revealed that fuel property values of waste-based feedstocks varied widely, indicating the importance of site specific feedstock analysis in system design.
- After gasification, arsenic from waste-based feedstocks was present in the gas phase at different levels depending on the use of gasification agents and bed materials. For example, when feedstock was gasified under oxygen, steam, and steam + oxygen conditions, 23 to 34% of the arsenic present in the feedstock was predicted to partition to the gas phase product stream. These values were reduced to 12% if bed material was included in the equilibrium gasification process calculations.
- Olivine bed material can help capture a portion of arsenic during the gasification process due to the presence of nickel in its chemical composition.
- Left unmanaged, arsenic species in the product gas stream are predicted to contribute to deactivation of Fe and Co based FT catalysts in downstream processes.
- It is possible to remove arsenic compounds by cooling hot product gas, however, cooling may also result in the condensation of high molecular weight compounds (tar).
- Copper and nickel can be employed as arsenic sorbents with sorptive capacity directly linked to the metal mass.

The study employed equilibrium calculations to analyze gasification and subsequent downstream processes. It is worth noting that real gasification systems are dynamic and considerably more complex to simulate. Experimental validation of these processes is thus recommended for further study.

Funding Source: DLA Energy

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Last Updated: November 2023

Hawai‘i Natural Energy Institute Research Highlights

Appendix E: Alternative Fuels

E3: Advanced Fuel Characterization and Development

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to systematically assess the impacts of trace quantities of heteroatomic organic species (HOS) on fuel properties and to advance the development of high-energy density (HED) fuels for future transportation applications.

New analytical methods under development can 1) evaluate the composition of fuels currently in use and those stored as strategic reserves and 2) 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 conventional petroleum and alternative fuels. The knowledge gained in this project will enhance our understanding of how HOS and fuel additives impact fuel stability and physicochemical properties, guide efforts to preserve fuel quality, reduce the cost of fuel characterization, and advance the development of alternative HED fuels.

BACKGROUND: Liquid fuels are, by nature, chemically complex and many fit-for-purpose and stability issues are associated with trace quantities of HOS inherent in the parent feedstock or employed as additives. Identification and quantitation of HOS and additives are challenging due to their low concentration and complex composition of the fuel matrix – necessitating the development and utilization of advanced analytical methods, such as two-dimensional gas chromatography (2D-GC).

In 2012, HNEI established a fuel laboratory with the capabilities encompassing essential analysis required by ASTM and military fuel specifications. Present capabilities include prediction of fuel properties using empirical and phenomenological modeling techniques. Research conducted in the fuel laboratory includes investigating the impacts of long-term storage, oxidative conditions, contaminants, additives, and other factors on conventional and alternative fuels and their blends. Computational methods to predict fuel properties support experimental efforts and contribute to the advancement of future transportation fuels.

In August 2018, a 2D-GC expanded the fuel laboratory's ability to identify and quantify fuel constituents present in trace amounts (≤1 ppm). The HNEI 2D-GC employs two injectors and three detectors, i.e. mass spectrometer (MS), nitrogen chemiluminescence (NCD) and sulfur chemiluminescence (SCD), to analyze fuel components and HOS with a single injection event. Neat fuels can be injected directly without requiring solvent dilution. Data generated using this instrument is used as input to the conductor-like screening model for realistic solvation (COSMO-RS) method. These calculation techniques predict physicochemical properties of petroleum and alternative fuels based on their individual compositions and guide the design of HED fuels.

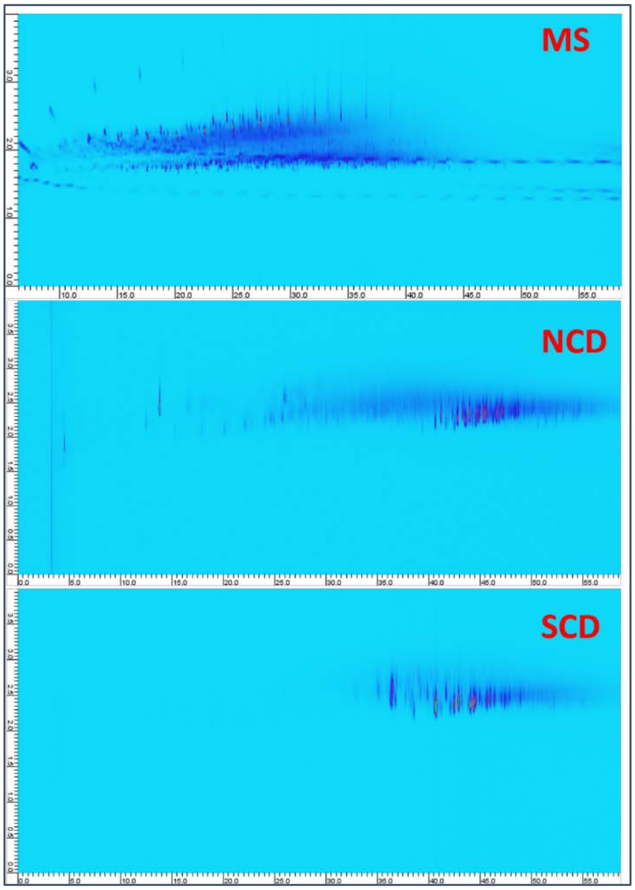

Figure 1. Comprehensive 2D-GC analysis of F-76 diesel fuel with MS, NCD, and SCD.

PROJECT STATUS/RESULTS: HNEI is currently collaborating with personnel from the Navy Technology Center for Safety and Survivability at the Naval Research Laboratory, Washington, DC on 2D-

GC applications for sulfur-containing compounds (SCCs) analysis.

Past activities under this project included: 1) participation in standard method development for nitrogen-containing compounds (NCCs) analysis with a 2D-GC-coupled NCD; 2) determining the impacts of antioxidant concentration on preserving fuel quality; and 3) COSMO-RS prediction of fuel boiling point, vapor pressure, density, and compatibility with fuel system polymers.

Currently, HNEI's activities include:

- Determining fuel hydrocarbon matrix;
- Exploring the influences of SCCs and NCCs on the degradation of fuel antioxidants (AOs) and the consequent impacts on fuel stabilities;
- Developing standard methods for identification and quantification of SCCs by using 2D-GC coupled to SCD and high resolution (HR) orbitrap MS;
- Calculating various fit-for-purpose properties based on the 2D-GC compositions of fuels; and
- Developing high energy density and stability fuels based on quantum chemistry and thermodynamic calculations.

To date, this project has produced the following publication:

- 2023, J. Fu, P.K. Le, S.Q. Turn, **Impacts of antioxidants on stability of biodiesel derived from waste frying oil**, *Biofuels, Bioproducts and Biorefining*, Vol. 17, Issue 6, pp. 1496-501.

Funding Source: Office of Naval Research

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Last Updated: November 2023

E4: Novel Biocarbons

OBJECTIVE AND SIGNIFICANCE: Biomass can be a renewable resource for the production of energy, fuels, chemicals, and materials. The goal of this project is to develop processes to 1) produce biochars and biocarbons from biomass feedstocks and 2) control and tune their properties by selection of biomass feedstocks and process conditions.

Slow pyrolysis is a thermochemical process that converts biomass into solid carbonaceous materials. The maximum temperature used during slow pyrolysis will dictate the extent to which the material is carbonized. Low temperature slow pyrolysis (200-500°C) results in the formation of biochar. High temperature slow pyrolysis (900-1200°C) produces biocarbon. The pyrolysis temperature is the dominant process parameter to control critical properties (e.g. volatile matter, carbon and fixed carbon contents, reactivity, surface area, density, tensile/compressive strength, grindability, etc.). One limitation to improving biochar/biocarbon properties is that biomass carbonization proceeds via a charring mechanism (no molten phase). The lack of a molten phase during carbonization limits the capacity to engineer critical material properties. Biochar and biocarbon have numerous applications including: fuel for cooking, adsorbents for air/water purification, a carbon sequestering soil amendment, and a carbon neutral coal/coke replacement in industrial applications. All are applicable in Hawaiʻi and can be produced from low value biomass materials.

BACKGROUND: Research at HNEI has identified certain constant-volume/pressurized reaction conditions that result in the formation of biochar with drastically altered morphology compared to the parent biomass. This unique biochar experiences a transient plastic phase (TPP) during carbonization, representing a new biomass carbonization pathway. The underlying mechanisms of TPP formation and utility are still being explored. The current research effort used parametric research design to independently study the effects of pressure, temperature, water content, and biomass type on the formation of TPP biochar. In addition to standard analytical tools (proximate analysis, true density, ultimate analysis), powder compaction experiments have been developed to characterize material plasticity and mechanical strength. These fundamental insights have been leveraged to increase biocarbon mechanical strength, a critical bottleneck for commercial applications.

PROJECT STATUS/RESULTS: Experimental results demonstrate that TPP formation proceeds through a molten phase. Elevated pressure serves to keep water in the condensed phase, inhibiting condensation reactions and enabling molten phase formation. TPP formation conditions were identified for a range of biomass types including hardwoods, softwoods, and herbaceous materials. Results from powder compaction experiments show that TPP biochar has increased plasticity along with a reduced glass transition temperature. Experiments comparing the mechanical strength of TPP and standard biocarbon materials show the TPP material is 10 times stronger, and twice as dense. Efforts to maximize the mechanical strength of TPP biocarbon achieved another 10x improvement, the strongest biocarbon material reported in the scientific literature (Figure 1). These mechanical properties exceed values required for numerous industrial applications. This novel production pathway overcomes technical barriers limiting biomass utilization as feedstock for biocarbons that can displace fossil carbon products. Potential applications include metallurgical reductants, binders, electrodes, or high value specialty materials. A preliminary patent application has been filed to protect this intellectual property and licensing negotiations are underway.

Figure 1. Biocarbon pellets produced from TPP biochar.

Funding Source: SINTEF Energy Research; Office of Naval Research

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Last Updated: November 2023

E5: Solar Fuels Generation

OBJECTIVE AND SIGNIFICANCE: The objective of this research is to improve the durability and efficiency of *chalcopyrite* and *perovskite* thin-film photo-absorbers for photoelectrochemical (PEC) production of *solar fuels*, aiming for a $1/kg production cost of renewable hydrogen.

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

Under two consecutive DOE awards received in 2014 and 2017, HNEI partnered with the University of Nevada, Las Vegas (UNLV), Stanford, the National Renewable Energy Laboratory (NREL), and Lawrence Livermore National Laboratory (LLNL) to establish a unique tool chest of *theoretical modeling*, *state-of-the-art synthesis*, and *advanced material and interface characterization* to provide deeper understanding of PEC materials and engineer high-performance devices. Focusing on the *chalcopyrite* material class, our group was able to synthesize solar absorbers capable of generating photocurrent densities relevant to high solar-to-hydrogen (STH) efficiencies (>12%). We also demonstrated that tungsten oxide (WO_3) films only few atoms thick could increase the stability of *chalcopyrites* in acid by a factor of 2 when compared to un-coated samples.

A key challenge remains: materials integration into “multi-junction” (MJ) PEC water splitting devices, an integration scheme in which thin film materials are monolithically stacked on top of each other to maximize STH efficiency. With such architecture, the deposition process of each layer must not damage the previously deposited layers and interfaces in any way. Our results showed that *chalcopyrites* are not compatible with monolithic MJ integration.

PROJECT STATUS/RESULTS: In 2023, HNEI and partners at Stanford, UNLV, LLNL and NREL received DOE funding to specifically develop a novel integration scheme in which material classes can be combined regardless of their nature while preserving their intrinsic performance. Such a scheme, pioneered by HNEI and known as *semi-monolithic* integration, relies on 2D materials-assisted exfoliation and room temperature bonding techniques to transfer fully integrated cells from their original substrates onto new handles. With this integration scheme, sub-cells can be successively transferred onto a new host to create a fully functional MJ structure. By design, semi-monolithic integration allows to circumvent all material incompatibilities, enabling new MJ architectures otherwise not possible with conventional monolithic integration. With this integration scheme, HNEI was able to fabricate the world’s first *chalcopyrite* triple junction PEC device with 3% STH efficiency (proof-of-concept). HNEI will leverage this new technology to combine *chalcopyrites* and *perovskites* photo-absorbers, aiming for MJ devices with STH efficiencies of at least 15%.

To date, this project has produced five peer reviewed papers, which are listed on the following page.

Funding Source: Department of Energy

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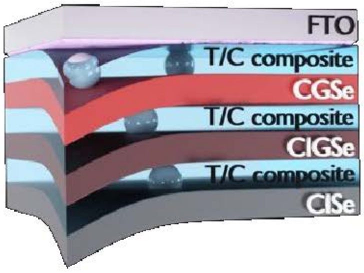
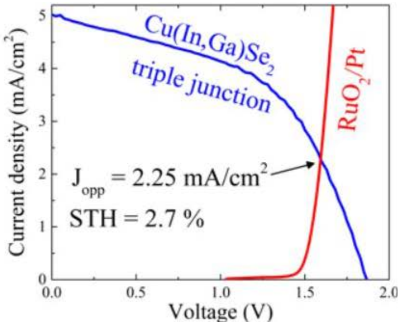
Last Updated: November 2023





ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

1. 2022, K. Outlaw-Spruell, J. Crunk, W. Septina, C.P. Muzzillo, K. Zhu, N. Gaillard, **Semi-monolithic Integration of All-Chalcopyrite Multijunction Solar Conversion Devices via Thin-Film Bonding and Exfoliation**, ACS Applied Materials and Interfaces, Vol. 14, Issue 49, pp. 54607-54615.
2. 2021, N. Gaillard, **A perspective on ordered vacancy compound and parent chalcopyrite thin film absorbers for photoelectrochemical water splitting**, Applied Physics Letters, Volume 119, Issue 9, Paper 090501.
3. 2021, I. Khan, C.P. Muzzillo, C.L. Perkins, A. Norman, J. Young, N. Gaillard, A. Zakutayev, **$Mg_xZn_{1-x}O$ contact to $CuGa_3Se_5$ absorber for photovoltaic and photoelectrochemical devices**, JPhys Energy, Vol. 3, Issue 2, Paper 024001. (Open Access: **PDF**)
4. 2021, D.W. Palm, C.P. Muzzillo, M. Ben-Naim, I. Khan, N. Gaillard, T.F. Jaramillo, **Tungsten oxide-coated copper gallium selenide sustains long-term solar hydrogen evolution**, Sustainable & Energy Fuels, Vol. 5, Issue 2, pp. 384-390.
5. 2020, A. Sharan, F.P. Sabino, A. Janotti, N. Gaillard, T. Ogitsu, J.B. Varley, **Assessing the roles of Cu- and Ag-deficient layers in chalcopyrite-based solar cells through first principles calculations**, Journal of Applied Physics, Vol. 127, Paper 065303.

E6: NELHA and MTA Hydrogen Stations and Fuel Cell Electric Buses

O<u>BJECTIVE AND</u> S<u>IGNIFICANCE</u>: In 2022, HNEI commissioned a 65kg/day hydrogen production and dispensing station on the Island of Hawaiʻi at the Natural Energy Laboratory Hawaiʻi Authority (NELHA) (Figure 1) and demonstrated on-site fueling of an electric-fuel cell hybrid bus. The overall 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 County of Hawaiʻi's clean transportation goals. The knowledge will also help inform decisions on other islands.

Figure 1. HNEI's NELHA hydrogen station.

B<u>ACKGROUND</u>: 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 (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. HNEI has delivered training to bus drivers and First Responders.

Figure 2. Concept for hydrogen transport on Hawaʻii Island.

P<u>ROJECT</u> S<u>TATUS</u>/R<u>ESULTS</u>:

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. The first fill of a hydrogen bus for public transportation took place on March 24, 2022.

Figure 3. HNEI's NELHA 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 and 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 trailer.

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 station 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 21-Passenger Fuel Cell Electric Bus: The Hele-On 21-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. Within the last year, 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 46 kW, a 15% improvement, and the range increased from 200 to 300 miles, a 50% improvement.

Figure 8. Hele-On 21-passenger FCEB.

Onboard hydrogen is stored in composite carbon fiber cylinders located under the bus with a capacity of 19 kg. The fuel cell power system is integrated with two 11 kWh (total 22 kWh) LG Lithium-ion battery packs to provide motive power to a 200 kW electric drive system. U.S. Hybrid replaced the original batteries with the new technology batteries using their 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. depending on the route topography and driver skills.

A 10 kW export power system (Figure 9) was installed in the 21-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 ~15 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 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 21-passenger FCEB. Onboard hydrogen capacity is 10 kg giving a projected range of 100 miles. These buses are being upgraded with 90 kW Hyundai fuel cells and one 33 kWh A123 Lithium-ion battery 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 proposed to be 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.

HNEI consulted with the MTA to select the location (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.

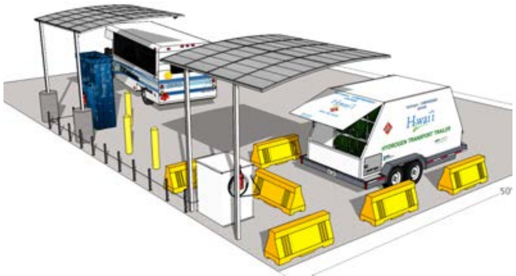


Figure 11. Concept design of MTA fueling dispensing station.

Figure 12. Concept of MTA site with fueling dispenser.

Hydrogen Station Energy Consumption: The total power consumption of the hydrogen system including the electrolyzer, compressor, and balance of plant is ~210 to 240 kW when operating at the maximum production rate of 65 kg/day (2.7 kg/hr). This corresponds to approximately 78 to 88 kwh/kg of compressed hydrogen. Figure 13 and Table 1 provides the breakdown of the observed power usage. This represents the largest single load on the NELHA research campus grid.

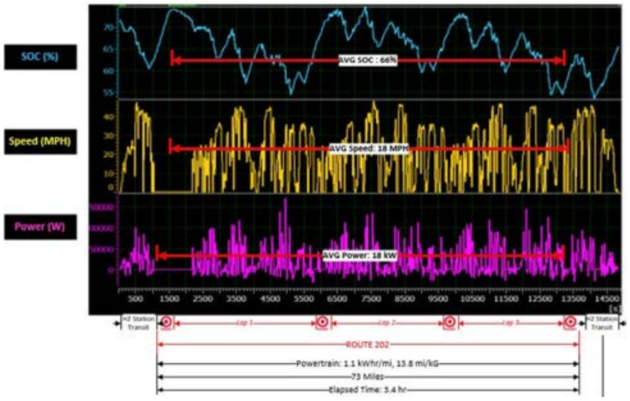


Figure 13. Observed performance data from the MTA FCEB.

Table 1. NELHA Hydrogen Station Observed Power Usage.

Electrolyzer in pre-start (no other equipment)	550	W
Electrolyzer in standby	740	W
Electrolyzer air cooler	260	W
Electrolyzer/Compressor room fans	800	W
Compressor Chiller	800	W
Electrolyzer filling/verifying A500 tank (air cooler)	850	W
Electrolyzer stack circulation state w/ air cooler	1.05	kW
A500 filling with electrolyzer room fan/air cooler	1.35	kW
Small compressor (only operates in short bursts)	1.5	kW
Full production with fans, compressor, chillers	210-240	kW

MTA FCEB Performance: The MTA buses are fitted with sensors and a data acquisition system that monitors bus system performance. Data is transmitted by cell phone telemetry to a remote computer. Outputs include powertrain energy consumption in kWh per mile and miles per kg of hydrogen. This data supports management of the bus fleet including identifying developing maintenance problems.

FTA Low/No Grant: In 2022, HNEI assisted the County of Hawaiʻi MTA in the development of their proposal resulting in a grant for $14 million from the Federal Transit Administration Low emissions/No emissions bus program. The funding will support the acquisition of six (6) new fuel cell electric buses and related infrastructure. MTA Administrator John Andoh stated that “the technical assistance of HNEI helped the MTA win this grant award”.

Public Outreach: On July 11, 2023, attendees of the “Meet the Bus” event (Figure 14) in West Hawaiʻi gathered for a photograph in front of the island’s first ever hybrid hydrogen electric bus. Hawaiʻi County Mayor Mitch Roth said, “look at what comes out of the vehicle – you don’t see smog; you just see water coming out. We’ve been looking at ways to have green energy, and hydrogen looks like the way of the future.”

Figure 14. “Meet the Bus” event on Hawaiʻi Island.

This project has produced the following papers:

- 2020, A. Headley, et al., **Valuation and cost reduction of behind-the-meter hydrogen production in Hawaiʻi**, 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 Hawaiʻi Hydrogen Fund; County of Hawaiʻi; Energy Systems Development Special Fund

Contact: Mitch Ewan, ewan@hawaii.edu; Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2023

F1: Contaminant Tolerant Fuel Cells for Harsh Environments

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. Contamination mechanisms in proton exchange membrane (PEM) fuel cells can become quite complex with many sources (air, fuel, system materials) and problems can be compounded by the contaminant reaction products that impact many key fuel cell materials.

BACKGROUND: 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 (HT-PEM) fuel cells have the benefits of higher contaminant tolerance and lower cost membranes vs. low temperature PEM 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) developed by NRL for creating custom catalyst coated membranes for small UAV scale fuel cells based on ultrasonic spray deposition and is adapting 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, and electrode structures designed for use in next-generation contaminant resistant fuel cells for UAVs.

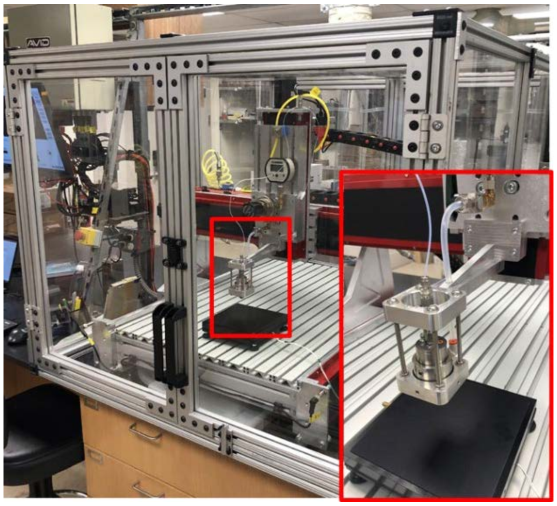


Figure 1. Ultrasonic spray coating system for in-house manufacturing of custom CCMs.

PROJECT STATUS/RESULTS: To date, we have performed literature review and identified optimal electrode structure of HNEI’s first generation HT-PEM membrane electrode assembly using readily available materials and began developing and evaluating fabrication protocols. Researchers also established collaborations with producers of the next generation of materials for high temperature fuel cells and began development of HNEI’s 2nd generation HT-PEM membrane electrode assembly.

Funding Source: Office of Naval Research

Contact: Keith Bethune, bethune@hawaii.edu

Last Updated: November 2023

ADDITIONAL PROJECT RELATED LINKS

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. 2022, Y. Garsany, R. E. Carter, M.B. Sassin, K. Bethune, and B. Gould, **Pairing Gas Diffusion Media for High-Power PEMFC Operation,** Presented at the ECS 2022-02 Meeting, Atlanta, Georgia, October 9-13, Abstract 1380.
2. 2020, Y. Garsany, C.H. Bancroft, R.W. Atkinson, K. Bethune, B.D. Gould, K. Swider-Lyons, **Operation of PEMFC Anodes in Dead-Ended Vs. Flow-through Modes**, Presented at the ECS 2020-02 Meeting, Honolulu, Hawai‘i, October 4-9, Abstract 2212.
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.

Hawai‘i Natural Energy Institute Research Highlights

Appendix F: Electrochemical Power Systems

F2: Anion Exchange Membrane Fuel Cell

OBJECTIVE AND SIGNIFICANCE: Interest in anion exchange membrane fuel cells (AEMFCs) is driven by the potential for lower cost and increased durability. The goals of this project are to 1) evaluate the performance of AEMFCs with platinum group metal (PGM) content and PGM-free cathode catalysts under various operating conditions, 2) study effects of membrane electrode assemblies (MEAs) components on mass transport, water management, and durability, and 3) develop electrochemical diagnostic and analysis methods applicable for AEMFC evaluation.

BACKGROUND: Interest in AEMFCs technology (Figure 1) has been driven by possible substitution of Pt electrocatalysts by platinum metal group (PGM)-free materials, since their performance in hydrogen oxidation and oxygen reduction in alkaline media is comparable or even higher than Pt. Moreover, operation in an alkaline environment is less corrosive and can improve durability.

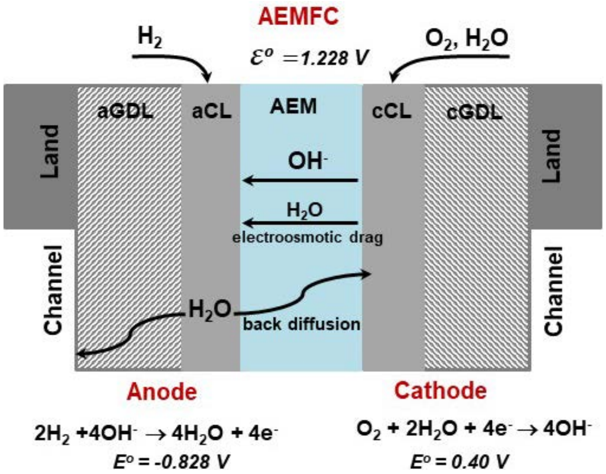


Figure 1. Schematic representation of AEMFC.

Design of MEAs for alkaline fuel cells is still in its infancy. Moreover, operation of AEMFC requires O_2 and water at the cathode, while water production happens at the anode; the situation is completely opposite compared to PEMFCs, which brings additional complexity and requirements to the MEA structure.

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. In addition, there is a lack of harmonized testing protocols and procedures and development of electrochemical diagnostics and approaches are critical for AEMFC.

PROJECT STATUS/RESULTS: Under this effort, HNEI has reached the following results:

- Established a capability to produce small size catalyst coated membranes and catalyst coated substrates, which gives opportunity for rapid evaluation of novel emerging materials available in the limited quantities;
- Established a break-in/start-up procedure after discussion with AEM manufactures and successfully tested;
- Identified critical parameters for Pt-based AEMFC MEAs, i.e., ionomer content and catalyst loading in anode and cathode; and
- Several pretreatment procedures of catalyst coated membranes were evaluated and the optimal pretreatment was identified.

Future work will include a continuation of electrochemical studies of AEMFCs with focus on MEAs reproducibility, durability, and performance.

Funding Source: Office of Naval Research

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Last Updated: November 2023

F3: 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.

BACKGROUND: The commercial application of a number of electrochemical technologies would benefit from the availability of low cost, efficient, and durable catalysts. Pt-group-metal catalysts are used in most commercially available fuel cells and water electrolyzers. Unfortunately, they have the short-comings of high cost, low earth abundance, and limited lifetime. Transition metal carbides are attractive candidates because they possess an electronic structure similar to Pt – which promotes high activities, good electrical conductivity, low cost, high abundance, and outstanding thermal and chemical stabilities. However, carbide synthesis is a challenge for achieving high surface area particles due to the inevitable aggregation during the high-temperature carburization.

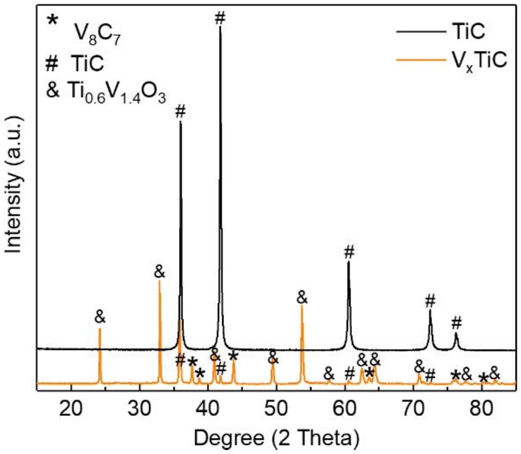

Figure 1. X-ray diffraction patterns.

PROJECT STATUS/RESULTS: This work is exploring a simple and environmentally friendly synthesis process for carbides that involve in situ carburization of a metal precursor and a carbon material. Considering the excellent electrochemical stability of TiC, the commercially available TiC was chosen as the carbon source and support to increase the stability of vanadium carbide. By modifying the synthesis and treatment approaches, V_xTiC was synthesized. As shown in Figure 1, V_xTiC contains Ti-V oxide $(Ti_xV_{1-x})_2O_3$, V_8C_7, as well as some unreacted TiC. V_xTiC exhibited excellent electrochemical stability up to 1.4 V (Figure 2) and better catalytic activity toward hydrogen evolution reaction (HER) than V_xC (Figure 3). Both V_xC and V_xTiC showed increased HER catalytic activity after up to 1.4V cycling.

Further electrochemical tests will be performed using carbides incorporated on carbon substrate as the working electrode. SEM/EDS will be used for morphological and elemental analysis. TEM will be used to investigate particle size and structure.

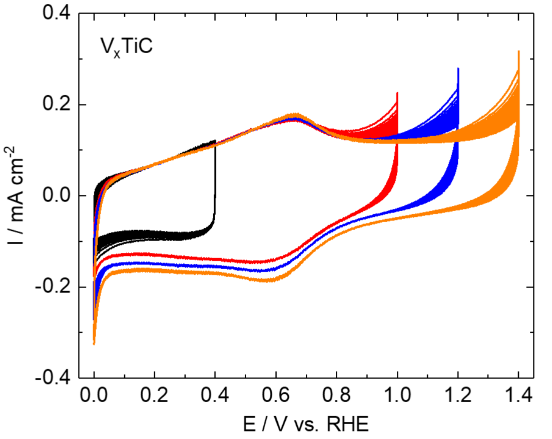

Figure 2. Cyclic voltammograms at 100mV s^{-1} in N_2-saturated 0.5M H_2SO_4 at 25°C.

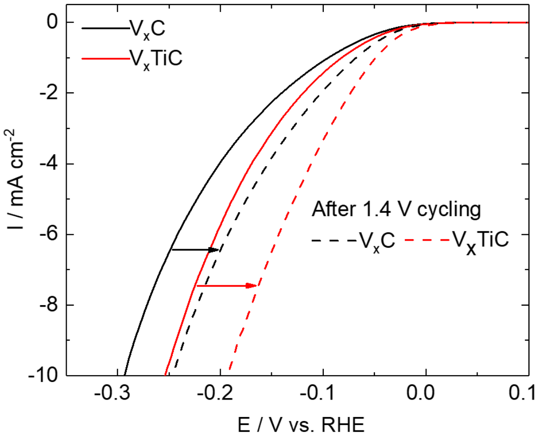

Figure 3. Polarization curves with a rotation rate of 1600rpm at 2mV s^{-1} in N_2-saturated 0.5M H_2SO_4 at 25°C.

Funding Source: Office of Naval Research

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Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix F: Electrochemical Power Systems

F4: Materials Enablers for Advanced Manufacturing of Attritable Fuel Cells

OBJECTIVE AND SIGNIFICANCE: Hydrogen fuel cell systems are ideally suited to power small unmanned systems that will be increasingly important when competing against near-peer adversaries, especially for isolated forces in the INDOPACOM region. A key facet of small unmanned systems is their attritability relative to expensive weapons systems. Attritable fuel cell powered unmanned systems require that the cost of fuel cells decrease so that their loss is acceptable in an exchange. This cost decrease can be traded against durability and performance, but ideally, both performance and durability would remain relatively constant. This is a uniquely DoD problem whose materials challenges are not being addressed by the broader fuel cell industry or academia.

The objective of this project is to perform material research combined with simulation to propose a conceptual design for a fuel cell with laminate construction to realize a 5x cost decrease over state-of-the art (SOA) small fuel cells (0.5-5 kW) while retaining performance.

BACKGROUND: Hydrogen fuel cells have the ability to store energy efficiently, produce electric power with low signature, and operate with minimum maintenance providing an important compliment to battery electric systems and internal combustion engines. Key advantages over the incumbent technologies are 4-8x gravimetric energy storage density over batteries, which translates into 4-8x endurance/range for systems and low signature DC power with improved start times over internal combustion engines. Key technical challenges remain for hydrogen fuel cells, namely cost, heat rejection, and volumetric storage density of hydrogen as compared to logistic fuels.

A large fraction of cost of system fabrication for small-scale fuel cells is associated with the bipolar plates and the labor costs associated with building the device because of the large part count. The objective of this work is to move fuel cell manufacturing closer to battery manufacturing, in which continuous reel-to-reel process are used to manufacture the electrode, which are then rolled or stacked into containers that require very little handwork or parts registration.

Under this work, HNEI is investigating the potential of high temperature proton exchange membrane fuel cells (HT-PEM) to develop materials enablers that will allow for the construction fuel cells with cheaper assembly costs through a simpler system architecture to reduce components. HT-PEM also has the potential to reduce the costs of precious metal catalysts and polymer membrane substrates to achieve the target cost reduction. The higher operating temperatures of HT-PEM directly addresses heat rejection challenges through higher temperature operation (120-200°C). Volumetric storage challenges of hydrogen are indirectly addressed in this project through a simpler fuel cell system architecture and increased heat rejection that leads to volume savings in the fuel cell system that can be applied to hydrogen storage space claim.

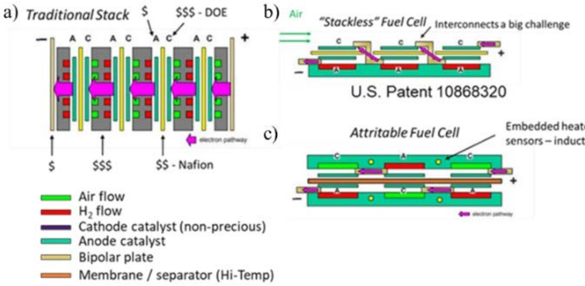

Figure 1. a) Traditional fuel cell stack with bipolar plate interconnects, b) previous demonstrated "Stackless Fuel Cell" by ONR, c) concept for a closed-cathode air-cooled fuel cell that would be attritable.

PROJECT STATUS/RESULTS: To date, we have down-selected components and fabrication protocols that yield peak power representative of the current art and began evaluating electrode fabrication techniques. Researchers have also designed and produced current collectors based on flexible circuit board technology and began planning for demonstrating operation with OEM and HNEI produced electrodes in a single cell. The year 1 results **Investigating the Suitability of Printed Circuit Components for Fuel Cells** were presented at the 244th Electrochemical Society meeting in October 2023.

Funding Source: Office of Naval Research

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Last Updated: November 2023

Hawai‘i Natural Energy Institute Research Highlights

Appendix F: Electrochemical Power Systems

F5: Proton Conducting Electrolytes for HT-PEMFC

<u>Objective and Significance</u>: The objective of this project is to develop a novel inorganic electrolyte with high proton conductivity under high temperature and low humidity to be used in the cathode catalyst layer of high temperature proton exchange membrane fuel cell (HT-PEMFC) to overcome the phosphoric acid (H_3PO_4) leaching issue. Operation of PEMFCs at HT would facilitate meeting U.S. Department of Energy’s (DOE) technical targets for performance, power and energy density, cost, and liability by inhibiting the poisoning effects of air pollutants and fuel impurities and simplifying the system’s water and heat management.

<u>Background</u>: PEMFCs are considered a promising clean energy technology for transportation and stationary applications. Contaminants in air and hydrogen fuel are a major challenge for the Pt catalysts in a typical PEMFC when it is operated in the realistic atmosphere. HT operation (150-200°C) of PEMFCs has been considered as one of the potential solutions to mitigate the poisoning effects due to the high conversion rate or weak adsorption of the contaminants. HT operation also facilitates the heat transport and the mass transfer of oxygen and hydrogen because the large temperature difference and the absence of liquid water in the cell, respectively. With those advantages, HT-PEMFCs would eliminate the humidifier and simplify the air and fuel supply and the cooling system. However, the current perfluorosulfonic acid (PFSA, Nafion®) polymer electrolytes are limited application below 90°C. The high temperature polymer PBI doped with H_3PO_4 (H_3PO_4/PBI) has been used as the PEM and the electrolyte in the catalyst layer of HT-PEMFC. However, H_3PO_4 leaching is a major issue during operation, especially from the cathode catalyst layer.

Recently, layered inorganic materials with “water in solid” have been developed as proton conducting electrolytes for the proton battery. The hydrogen bond switching among the ligand water provides a fast proton transport network in mutilayer structures (Figure 1). The proton conducting materals can also be used in the catalyst layers of the HT-PEMFC.

<u>Project Status/Results</u>: At HNEI, novel inorganic layered structure materils are being developed as proton conducting electrolyte. The candidate will be integrated into the in the cathode of HT membrane electrode assemblies (MEAs) of the contaminant tolerant FCs for harsh environments.

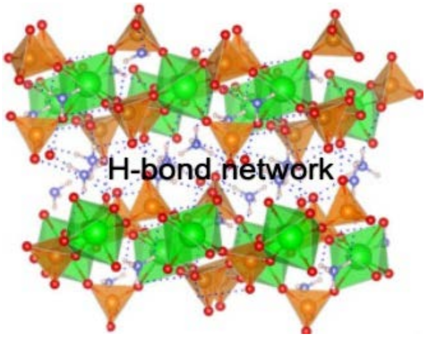

Figure 1. H-bond network in the layered structures of the inorganic proton conducting materials.

Currently, the proton conducting electrolyte powders (Figure 2a) were obtained by a fluxing method. The production yield was improved from ~5% to ~50% by optimizing the conditions of synthesis. With the preliminary tests, the electrolyte powder pellet (Figure 2b and 2c) shows a bulk proton conductivity of ~10^{-3} Scm^{-1} and a particles boundary conductivity of ~10^{-5} Scm^{-1} in the range of from room temperature to 150°C (Figure 3). The conductivity increases with the rise of temperature.

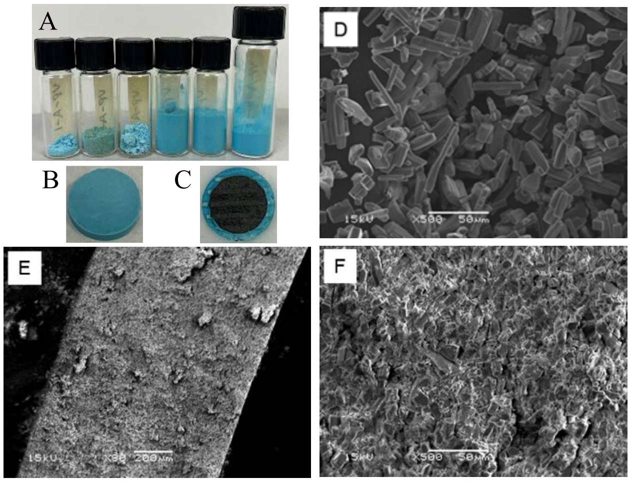

Figure 2. The pictures of the proton conductor powders (A) and the pellet (B, C). and the SEM images of the powders (D) and the cross-section of the pellet (E, F).

Additionally, with collaboration of industrial and academic partners, a proposal titled with “High Performing and Durable MEAs with Novel Electrode Structures and Hydrocarbon Proton Exchange Membranes” was submitted to the U.S. DOE for addressing: Hydrogen and Fuel Cell Technologies

Office FOA in Support of Hydrogen Shot (DE-FOA-0002920), Topic Area 4: High Performing and Durable Membrane Electrode Assemblies for Medium- and Heavy-Duty Applications. The proposed research was selected for a $4M award in three years.

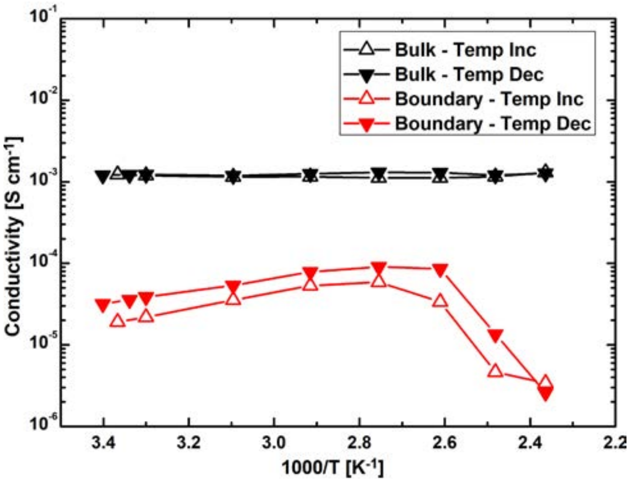

Figure 3. The bulk and boundary proton conductivity of the proton conducting particles at temperature 20-150°C.

In the future, HNEI plans to characterize the materials structures, composition and stability. The properties and performance of the materials will be further studied and improved with the optimization the synthesis procedures. The selected materials will be integrated into the cathode catalyst layers of HT-MEAs. The performance of HT-PEMFC with new proton conductive materials will also be evaluated at 150-200°C.

Funding Source: Office of Naval Research

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Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix F: Electrochemical Power Systems

F6: Advanced Characterization of PEMFC with Open Flow Field Architecture

OBJECTIVE AND SIGNIFICANCE: Proton exchange membrane fuel cells (PEMFCs) are energy conversion devices that offer high power densities at low operating temperatures making PEMFCs the most promising technology for many applications, such as automobiles, back-up power generating units, and portable devices. Commercial PEMFC systems utilize open flow field (OFF) architectures ensuring high power generation and excellent performance at high currents. The project objective is to conduct a detailed evaluation of PEMFCs employing OFF design using advanced approaches like electrochemical impedance spectroscopy (EIS) and segmented cell system.

BACKGROUND: Application of a conventional land-channel flow field architecture for PEMFC results in non-uniform performance over the active area of membrane electrode assembly (MEA) due to incremental O_2 consumption from air stream, water production and accumulation. These results lead to higher performance of the inlet of the fuel cell and lower performance at the outlet. In order to address this nonhomogeneous performance, open flow field architecture is applied for commercial PEMFCs (Figure 1). The main benefits of metal based OFF are its high durability and cost-effectiveness. Moreover, OFF increases utilization of MEA geometrical area.

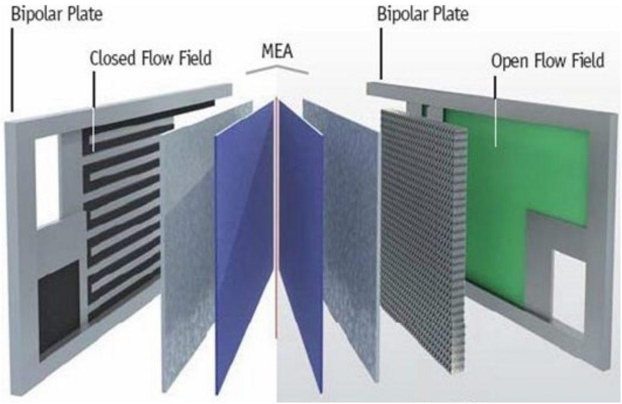

Figure 1. Schematic representation of fuel cell with open flow field.

Previously, HNEI developed a segmented cell system to study non-uniform phenomena in a working fuel cell. The segmented cell system allows us to record current/voltage/impedance responses from 10 segments simultaneously and provide valuable information on local performance (Figure 2).

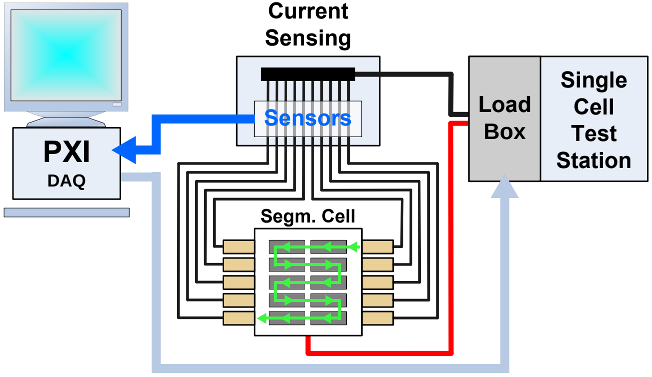

Figure 2. Schematic of segmented cell system.

PROJECT STATUS/RESULTS: Under this effort, HNEI has reached the following results:

- Demonstrated feasibility of incorporation of the OFF to HNEI's segmented cell system;
- OFF ensured uniform performance over MEA compared to the conventional land-channel flow field architecture;
- OFF demonstrated superior performance than the land-cannel flow field especially in high power generating conditions; and
- OFF ensures better heat transfer and dissipation, which is important for operation at high current.

Future work will include a continuation of studies of PEMFCs with the OFF.

Funding Source: Nuvera Fuel Cells

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Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix F: Electrochemical Power Systems

F7: Proton Exchange Membrane Fuel Cell Producing Hydrogen Peroxide

OBJECTIVE AND SIGNIFICANCE: Hydrogen peroxide is widely useful to many industries, as well as the military, as an environmentally friendly disinfectant and liquid oxidant for air-independent fuel cell applications. The main method for hydrogen peroxide production today: an anthraquinone-oxidation process, is energy-intensive, expensive, produces waste that negatively impacts the environment, and is not easily scalable, leading to the transport of dilute solutions at high cost to minimize safety concerns. The objective of this project is modify a proton exchange membrane fuel cell (PEMFC) to develop an alternative, electrochemical method for synthesizing hydrogen peroxide that also produces energy, eliminates waste by producing aqueous solutions of varied hydrogen peroxide concentrations, and is scalable to address the specific needs of these various industries and communities.

BACKGROUND: Hydrogen peroxide is considered among the world's top 100 most important chemicals as it is very versatile and is mainly an eco-friendly disinfectant. Today, over 95% of hydrogen peroxide is produced from an anthraquinone-oxidation process. This process is very costly, mainly due to the fact that it can only economically work at large-scale. Further, it is a batch process that requires further separation and dilution processes, which also necessitate enormous amounts of energy to conduct. These dilution processes are vital as a safety measure to transport hydrogen peroxide over a range of distances due to its explosive nature as an oxidant. The substantial risks associated with the transportation of hydrogen peroxide alone produces a major need for scalable, onsite production of this chemical. If successful, onsite production of hydrogen peroxide would also provide the means for wastewater treatment in rural communities.

Hydrogen peroxide can be synthesized electrochemically from hydrogen and oxygen in a fuel cell utilizing the 2-electron (e^-) pathway of the oxygen reduction reaction (ORR) (Equation 1). Most polymer electrolyte (PEM) fuel cell research involves the $4e^-$ pathway of the ORR, or complete reduction of oxygen which produces water and power (Equation 2).

$$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2 \quad \text{(Equation 1)}$$
$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad \text{(Equation 2)}$$

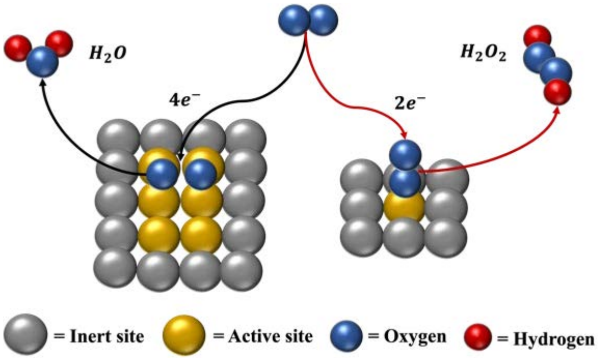

Figure 1. $2e^-$ and $4e^-$ pathways for the ORR.

PROJECT STATUS/RESULTS: The experimental plan and detailed procedures developed for a selective catalyst for the $2e^-$ pathway (further referred to as the "nano-dispersed supported-catalyst" or NDSC) was implemented and verified experimentally in a rotating ring/disk electrode (RRDE) setup. Results have shown that the modified NDSC is stable for a minimum of 22 hours under harsh experimental conditions.

Polarization curves were measured for both the ring and disk currents produced during experimentation with the NDSC. Hydrogen peroxide and water are generated at the disk whereas hydrogen peroxide is selectively detected at the ring. Ring current data versus time and disk potential from both the unmodified and modified NDSC are presented in Figure 2.

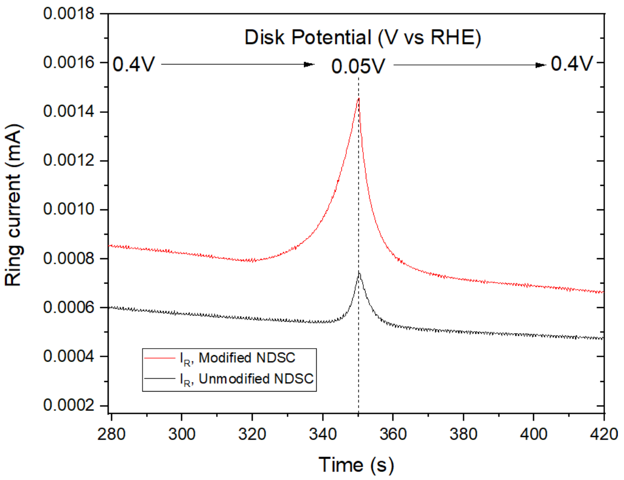

Figure 2. Ring current versus time and disk potential (0.05-0.4V vs RHE) for unmodified and modified NDSC indicating a significant increase at low disk-potentials (peak region).

The larger peak produced in the ring current for the modified NDSC (red) compared to that of the unmodified NDSC (black) at a low disk-potential (0.05V vs. the Reversible Hydrogen Electrode (RHE)) indicates that the catalyst modification is beneficial with an increase exceeding 100%. It is noted that the ring signal indirectly shows the presence of hydrogen peroxide at the ring electrode.

Preliminary hydrogen peroxide detection tests by colorimetry were performed to directly confirm the presence of hydrogen peroxide produced at the disk. Figure 3 shows the result of a colorimetric test, which confirmed the presence of approximately 3 mg/L hydrogen peroxide within the bulk solution after completion of experimental procedures.

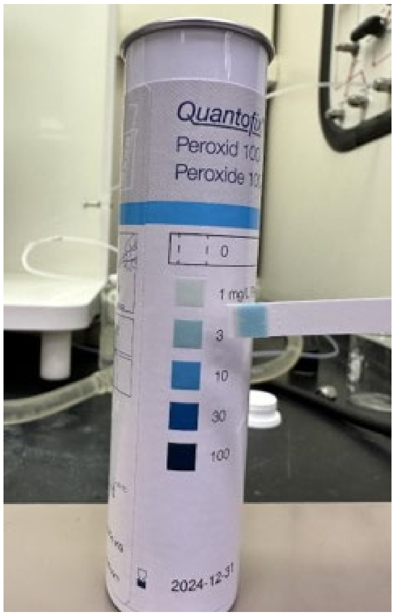

Figure 3. Colorimetric test strip indicating the positive detection of hydrogen peroxide after insertion into the bulk solution (post-production test).

HNEI is developing a quantitative potentiometric titration technique for a more precise detection of hydrogen peroxide in the bulk solution after experimentation with modified NDSCs. HNEI will complete long-term RRDE experiments under a range of conditions aimed at maximizing the hydrogen peroxide yield and characterizing catalyst stability. Finally, experiments will be conducted in a single, 50 cm^2 PEMFC specifically modified (including changes in both operating conditions and hardware design) to simultaneously maximize peroxide yield and minimize peroxide decomposition within the cell. Other performance metrics will also be monitored during these tests, including exhaust composition and cell power for optimization of hydrogen peroxide production and electrical power.

Funding Source: Office of Naval Research

Contact: Alexandra Fernandez, af41@hawaii.edu

Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix F: Electrochemical Power Systems

F8: Path Dependence of Battery Degradation

Objective and Significance: 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 informs best practices to successful battery durability, safety, fast charging, or vehicle-to-X integration.

Background: 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.

Project Status/Results: Our study already showed that a simplistic approach to V2G, namely that an EV is discharged at constant power for 1 hour 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 durability and reliability in the field. Collaborative work is also ongoing with Sandia National Laboratories and Aalborg University (Denmark).

Research conducted for this project is completed in the **PakaLi Battery Laboratory**. This project is ongoing and has led to 11 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

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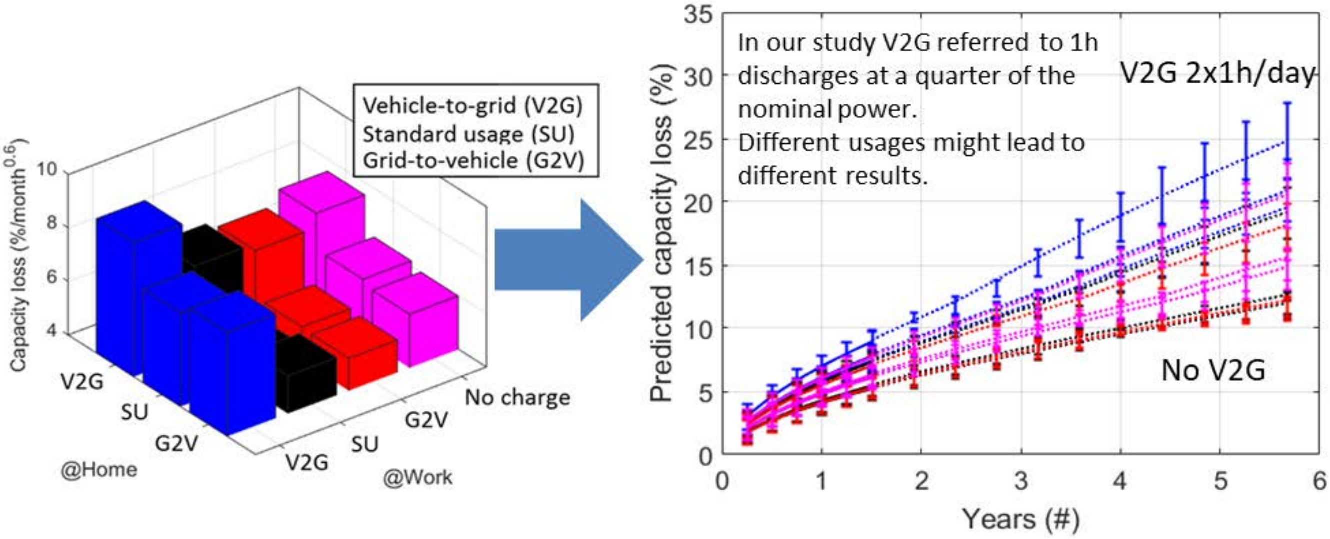


In our study V2G referred to 1h discharges at a quarter of the nominal power.
Different usages might lead to different results.

ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

1. 2022, P.M. Attia, et al., **Review—"Knees" in Lithium-Ion Battery Aging Trajectories**, Journal of The Electrochemical Society, Vol. 169, Issue 6, Paper 060517. (Open Access: **PDF**)
2. 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**)
3. 2020, M. Elliott, et al., **Degradation of electric vehicle lithium-ion batteries in electricity grid services**, Journal of Energy Storage, Vol. 32, Paper 101873.
4. 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**)
5. 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**)
6. 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**)
7. 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**)
8. 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.
9. 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.
10. 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.
11. 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. 2022, R. Wittman, et al., **Path Dependence of Li-Ion Battery Degradation During Cycling to 80% Capacity**, Presented at the Material Research Society Spring Meeting, May 8-13.
2. 2021, R. Wittman, et al., **Characterizing Materials and Electrochemical Changes in a Range of 18650 Li-Ion Cells Cycled to 80% Initial Capacity**, Presented at the 239th ECS Meeting, Chicago, IL, May 30-June 3.
3. 2019, M. Dubarry, et al., **Synthetic vs. Real Driving Cycles: A Comparison of EV Battery Degradation**, Presented at the 236th ECS Meeting, Atlanta, Georgia, October 13-17.
4. 2019, G. Baure, et al., **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.
5. 2017, A. Devie, et al., **Durability and Reliability of EV Batteries under Electric Utility Grid Operations**, Presented at the 232nd ECS Meeting, National Harbor, Maryland, October 1-5.
6. 2016, M. Dubarry, et al., **Path Dependence in Lithium-Ion Batteries Degradation**, Presented at the ECS PRiME Meeting, Honolulu, Hawaiʻi, October 2-7.
7. 2016, M. Dubarry, et al., **EV Cell Degradation under Electric Utility Grid Operations**, Presented at the Next-Generation Energy Storage Conference, San Diego, California, April 18-19.
8. 2015, M. Dubarry, et al., **Experimental diagnostic of Li-ion commercial cells, case studies**, Presented at the 225th ECS Meeting, Orlando, Florida, May 11-15.

Hawaiʻi Natural Energy Institute Research Highlights

Appendix F: Electrochemical Power Systems

F9: 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 in diagnosing and prognosing 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. Recent work highlighted the possible opportunistic diagnosis of battery usage for photovoltaic-connected batteries using models trained and validated on synthetic datasets.

Research conducted for this project is completed in the **PakaLi Battery Laboratory**.

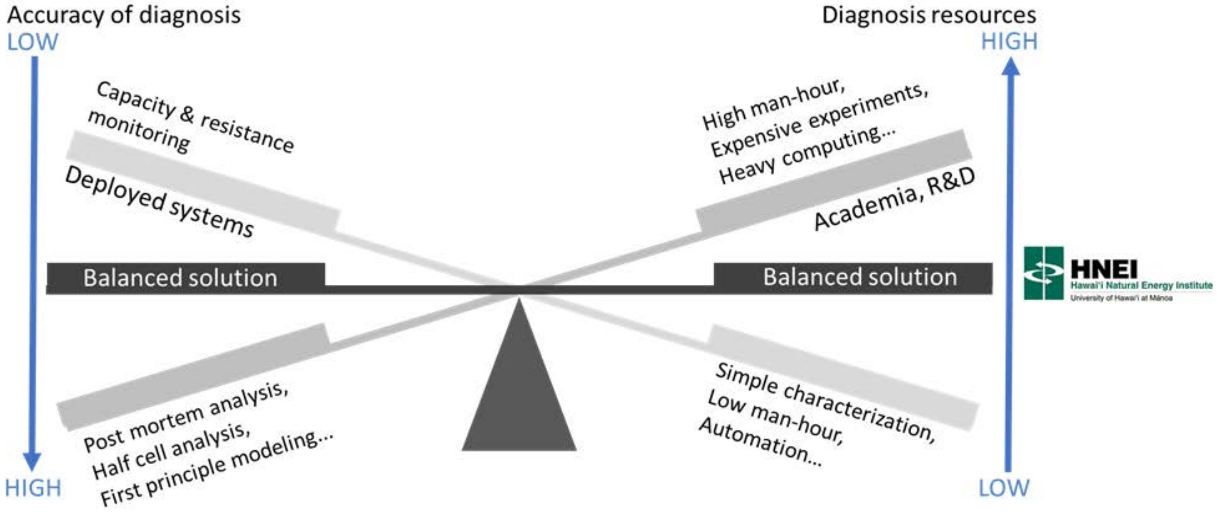
PROJECT STATUS/RESULTS: This project is currently ongoing with three industrial collaborations on different aspects of the problem. A full suite of software and models were developed. The main model has been licensed by more than 125 organizations worldwide.

This work has also led to 45 publications, many of which are linked on the following pages, and one patent.

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

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2023



ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

Battery Testing

1. 2022, M. Dubarry, et al., **Best practices for incremental capacity analysis**, Frontiers in Energy Research, 10:1023555. (Open Access: **PDF**)
2. 2022, L. Ward, et al., **Principles of the Battery Data Genome**, Joule, Vol. 6, Issue 10, pp. 2253-2271. (Open Access: **PDF**)
3. 2022, N. Costa, et al., **Li-ion battery degradation modes diagnosis via Convolutional Neural Networks**, Journal of Energy Storage, Vol. 55, Part C, Paper 105558. (Open Access: **PDF**)
4. 2022, P.M. Attia, et al., **Review—"Knees" in Lithium-Ion Battery Aging Trajectories**, Journal of The Electrochemical Society, Vol. 169, Issue 6, Paper 060517. (Open Access: **PDF**)
5. 2021, M. Dubarry, et al., **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**)
6. 2020, M. Dubarry, et al., **Big data training data for artificial intelligence-based Li-ion diagnosis and prognosis**, Journal of Power Sources, Vol. 479, Paper 228806.
7. 2020, D. Anseán, et al., **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.
8. 2020, M. Dubarry, et al., **Perspective on Commercial Li-ion Battery Testing, Best Practices for Simple and Effective Protocols**, Electronics, Vol. 9, Issue 1, Paper 152. (Open Access: **PDF**)
9. 2019, A. Barai, et al., **A comparison of methodologies for the non-invasive characterisation of commercial Li-ion cells**, Progress in Energy and Combust. Sci., Vol. 72, pp. 1-32. (Open Access: **PDF**)
10. 2018, M. Dubarry, et al., **Calendar aging of commercial Li-ion cells of different chemistries – A review**, Current Opinion in Electrochemistry, Vol. 9, pp. 106-113.
11. 2018, A. Devie, et al., **Intrinsic Variability in the Degradation of a Batch of Commercial 18650 Lithium-Ion Cells**, Energies, Vol. 11, Issue 5, Paper 1031. (Open Access: **PDF**)
12. 2018, C.T. Love, et al., **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**)
13. 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.
14. 2016, D. Ansean, et al., **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. 2023, M. Dubarry, et al., **Data-Driven Diagnosis of PV-Connected Batteries: Analysis of Two Years of Observed Irradiance**, Batteries, Vol. 9, Issue 8, Paper 395. (Open Access: **PDF**)
2. 2023, M. Dubarry, et al., **Accurate LLI and LAM_{PE} Estimation Using the Mechanistic Modeling Approach with Layered Oxides**, Journal of The Electrochemical Society, Vol. 170, Paper 070503. (Open Access: **PDF**)
3. 2023, M. Dubarry, D. Howey, B. Wu, **Enabling battery digital twins at the industrial scale**, Joule, Vol. 7, Issue 6, pp. 1134-1144. (Open Access: **PDF**)
4. 2023, M. Dubarry, N. Costa, D. Matthews, **Data-driven direct diagnosis of Li-ion batteries connected to photovoltaics**, Nature Communications, Vol. 14, Paper 3138. (Open Access: **PDF**)
5. 2022, M. Dubarry, et al., **Perspective on Mechanistic Modeling of Li-Ion Batteries**, Accounts of Material Research, Vol. 3, Issue 8, pp. 843-853.
6. 2019, S. Schindler, et al., **Kinetics accommodation in Li-ion mechanistic modeling**, Journal of Power Sources, Vol. 440, Paper 227117.

7. 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**)
8. 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**)
9. 2017, M. Dubarry, et al., **State of Health Battery Estimator Enabling Degradation Diagnosis: Model and Algorithm Description**, Journal of Power Sources, Vol. 360, pp. 59-69.
10. 2016, M. Dubarry, et al., **Cell-balancing currents in parallel strings of a battery system**, Journal of Power Sources, Vol. 321, pp. 36-46.
11. 2016, M. Berecibar, et al., **Degradation Mechanism Detection for NMC Batteries based on Incremental Capacity Curves**, World EV Journal, Vol. 8, Issue 2, pp. 350-361. (Open Access: **PDF**)
12. 2016, M. Berecibar, et al., **Online State of Health estimation on NMC cells based on Predictive Analytics**, Journal of Power Sources, Vol. 320, pp. 239-250.
13. 2016, M. Berecibar, et al., **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.
14. 2015, M. Berecibar, et al., **SOH estimation and prediction for NMC cells based on degradation mechanism detection**, Proceeding of the IEEE Vehicle Power and Propulsion Conference (VPPC), INSPEC 15678053.
15. 2015, M. Dubarry, et al., **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. 2023, M. Dubarry, et al., **Effect of Temperature on Lithium-Ion Battery Voltage Response and How to Model It in the Mechanistic Modeling Approach**, Presented at the 244th Electrochemical Society Meeting, Goteborg, Sweden, October 8-12.
2. 2023, M. Dubarry, et al., **Big data for the diagnosis and prognosis of deployed energy storage systems**, Presented at the Energy Storage Systems Safety & Reliability Forum, Santa Fe, NM, June 6-8.
3. 2023, A. Fernando, et al., **A Study of the Relaxation Patterns of Commercial Cells**, Poster presented at the International Battery Association Conference, Austin, TX, March 5-10.
4. 2022, M. Dubarry, **Big Data in Diagnostics Data-Driven Direct Diagnosis of PV Connected Batteries**, Presented at the Advanced Automotive Battery Conference, San Diego, California, December 7-9.
5. 2022, M. Dubarry, et al., **Mechanistic Li-Ion Battery Modeling, What's Next?**, Presented at the 242th ECS Meeting, Atlanta, GA, October 9-13.
6. 2022, M. Dubarry, **Battery energy storage system modeling: A combined comprehensive approach**, Presented at the IEEE Power & Energy Society General Meeting, Denver, CO, July 17-21.
7. 2022, M. Dubarry, et al., **Big Data for Li-Ion Battery Diagnosis and Prognosis**, Presented at the Material Research Society Spring Meeting, May 8-13.
8. 2021, M. Dubarry, et al., **A New Insight into Blended Electrodes**, Presented at the 240th ECS Meeting, Orlando, Florida, October 10-14.
9. 2020, M. Dubarry, et al., **Synthetic Training Data for Artificial Intelligence-Based Li-Ion Diagnosis and Prognosis**, Presented at the ECS PRiME Meeting, October 4-9.
10. 2017, M. Dubarry, **Non-intrusive operando battery diagnosis and prognosis**, Presented at the Pacific Rim Conference on Ceramic and Glass Technology Meeting, Waikoloa, Hawai‘i, May 21-26.
11. 2016, D. Anseán, et al., **Lithium Plating Quantification in Commercial Graphite‖$LiFePO_4$ Batteries**, Presented at the ECS PRiME Meeting, Honolulu, Hawai‘i, October 2-7.
12. 2015, A. Devie, et al., **Intrinsic degradation variability in commercial lithium-ion batteries**, Presented at the 228th ECS Meeting, Phoenix, Arizona, October 11-16..

Hawaiʻi Natural Energy Institute Research Highlights

Appendix F: Electrochemical Power Systems

F10: 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 battery diagnosis as well as Designs of Experiments (DoE) to optimize formulations and to investigate the importance of process parameters while minimizing resources.

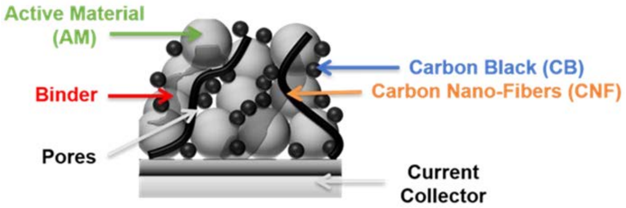


Figure 1. Schematic of the typical electrode architecture for intercalation-based batteries.

Defining new approaches to minimize experiments and time to reach an optimal battery electrode composition is highly beneficial to the field. To this end, we used a DoE mixture design that 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 was 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 then ONR 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 15,000 times with improved performance compared to traditional materials (CDI).

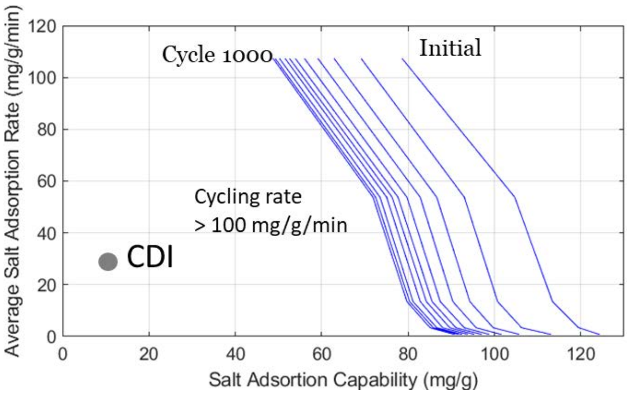


Figure 2. Performance characteristics of novel intercalation materials for desalination batteries.

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

Research conducted for this project is completed in the **PakaLi Battery Laboratory**. This program led to the three publications and a proceeding, which are listed on the following page).

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

Collaborations: University of Montreal (Canada); University of Nantes (France); Naval Research Laboratory; Sandia National Laboratories

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2023

ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

1. 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**)
2. 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.
3. 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.
4. 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**)

PRESENTATIONS:

1. 2023, C.T. Love, et al., **Evidence of the Interplay of Temperature on Local and Global Battery Phenomena**, presented at the 244th Electrochemical Society Meeting, October 8-12. *Keynote presentation*.
2. 2022, N. Sahin, et al, **Optimization of Prussian Blue Analogues for Na-Ion Desalination Batteries**, Poster presented at the Material Research Society Spring Meeting, May 8-13. *Best poster award Symposium EN05.*
3. 2022, C. T. Love, et al., **How Dynamic Thermal Evaluation of Battery Electrodes and Materials Better Replicate In-Service Operating Conditions**, Presented at the Material Research Society Spring Meeting, May 8-13.
4. 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.
5. 2021, C. T. Love, et al., **Electrode Specific Degradation Tailored By the Directionality of Thermal Gradients in Li-Ion Batteries**, Presented virtually at the 240th ECS Meeting, Orlando, FL, October 10-14.
6. 2021, C. T. Love, et al., **Directionality of Thermal Gradients in Li-Ion Batteries Dictates Diverging Failure Modes**, Presented virtually at the 239th ECS meeting, Chicago, IL, May 30 - June 3.
7. 2019. O. Rynne, et al., **Influence of the Formulation on the Microstructure and Thus Performance of Li-Ion Batteries**, Presented at the 235th ECS Meeting, Dallas, TX, May 26-30.

G1: 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 reduce manufacturing costs and enable PV integration on non-conventional substrates such as polyamides or woven fabrics.

BACKGROUND: Crystalline silicon has been leading the PV market for over 20 years. These panels, found 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 for both civilian and military applications, such as phones, electronic tablets, and sensors.

PROJECT STATUS/RESULTS: With support from the Office of Naval Research, the research team at HNEI's Thin Films Laboratory is developing a unique method to print thin-film PV using liquid molecular inks, which contain the raw chemical elements necessary for the synthesis of the solar absorber. This low-cost printing process is intended to replace conventional vacuum-based deposition tools, which are costly to operate and maintain.

Our research 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. HNEI's 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, HNEI demonstrated that additives directly incorporated into the molecular ink, such as aluminum nitrate, can passivate native defects in CISe during fabrication, yielding to efficiency as high as 11%. Using state-of-the-art electron microscopy analysis available at UH, the HNEI team discovered that aluminum nitrate reacted with oxygen during CISe growth to form nano-sized amorphous alumina (Al_2O_3) grains. This new process was found to incorporate Al_2O_3 through the entire solar absorber's volume, passivating defects notably at grain boundaries and interfaces.

To date, this project has produced the following paper:

- 2021, W. Septina, et al, ***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

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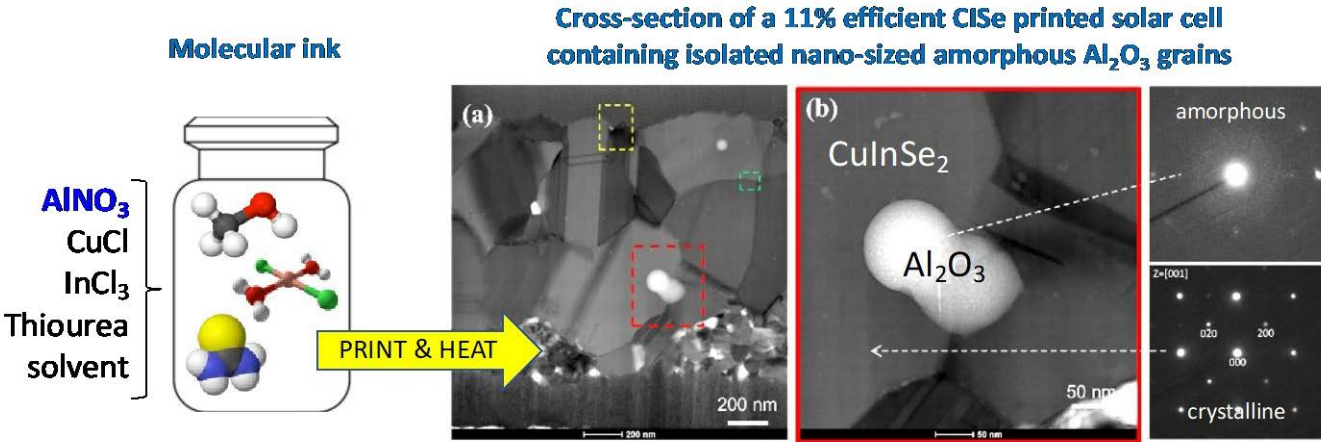
Last Updated: November 2023



Hawaiʻi Natural Energy Institute Research Highlights

Appendix G: Advanced Materials

G2: Two-Dimensional Materials for Thin Film Manipulation

OBJECTIVE AND SIGNIFICANCE: Through this program, our objective is to enhance our understanding of interfaces formed between thin film materials and two-dimensional (2D) layers. We strive to explore the potential of these interfaces in physically manipulating thin films and innovating renewable energy conversion devices.

BACKGROUND: Monolithic integration – the process by which solid-state devices are made by sequentially depositing layers of materials on top of each other – is used in all commercial thin film-based technology. This process is so foundational that it is difficult to imagine any other way to create solid-state devices. Despite its wide acceptance, however, monolithic integration presents two major limitations. First, process compatibility is a challenge since the deposition of each layer must not damage the previously deposited underlying layers in any way. As such, the thermal, mechanical, and chemical compatibility between layers and their deposition processes is of prime importance, restricting materials selection to a sub-set of compatible systems and limiting the adoption of emerging promising candidates. Second, monolithic integration almost always leads to the formation of additional phases at the interface of two materials. The electronic and chemical properties of interfaces also generally differ significantly from those of a simple combination of the two constituting layers, impacting device performance.

An integration scheme that combines materials regardless of their nature, while preserving or even enhancing their intrinsic performance, could revolutionize manufacturing of renewable technologies that rely on material stacking, including photovoltaic (PV) devices. Such an integration approach – using 2D materials for thin film manipulation – is proposed in this program.

In this project, the University of Hawaiʻi (UH) and the University of Nevada, Las Vegas (UNLV) partnered with the Lawrence Livermore National Laboratory (LLNL) and National Renewable Energy Laboratory (NREL) to develop the concept of 2D material-assisted thin film exfoliation, focusing on the chalcopyrite class (e.g., Cu(In,Ga)Se_2, CIGSe) and transition metal dichalcogenides (e.g., MoS_2 and $MoSe_2$) 2D interfacial layers that can naturally form when sulfur- or selenium-containing semiconductors are deposited onto transition metal substrates.

PROJECT STATUS/RESULTS: Current efforts are focused on: 1) the exfoliation of commercially available 2D materials; 2) the characterization of their chemical properties using advanced spectroscopic techniques; and 3) the theoretical modeling of their energetics when interfaces with CIGSe. Graphene and $MoSe_2$ 2D layers were isolated through the mechanical exfoliation method. Flakes of both materials were delaminated from bulk seed crystals by pressing a transfer strip onto them. The process involved folding the tape on itself a predetermined number of times to further separate the remaining crystals. Subsequently, these separated layers were transferred onto silicon wafers. X-ray photoelectron spectroscopy and Raman spectroscopy carried out at UNLV and HNEI, respectively, evidenced the 2D nature of the layers isolated with HNEI's method. Lastly, theoretical modeling efforts conducted at both UH and LLNL focused on understanding the impact of mechanical strain on the energetic properties of 2D materials. This crucial information will be instrumental in analyzing how mechanical deformation, such as stretching or bending, affects the performance of PV devices.

Funding Source: Department of Energy

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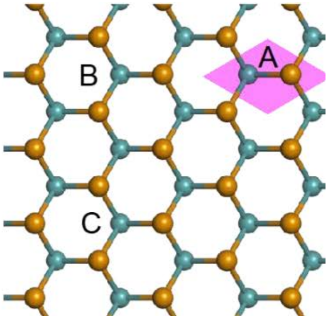
Last Updated: November 2023



G3: Encapsulation of Perovskite Solar Cells for Long Term Operations

OBJECTIVE AND SIGNIFICANCE: The objective of this program is to extend the lifetime of low-cost, high efficiency perovskite solar cells (PSCs) to meet the U.S. Department of Energy's 2030 cost target of \$0.02/kWh.

BACKGROUND: Since the first report of PSCs in 2009, tremendous research efforts on absorber chemistry have boosted the power conversion efficiency of this material class from 3.9% to 25.7%. Although impressive, this attribute alone cannot guarantee the commercial success of PSCs, as any emerging technology must also meet the 20-25 year stability already achieved by other mature photovoltaic (PV) classes. To date, the durability of best performing PSCs is limited to few months at best, constituting an important roadblock in their deployment. In this project, HNEI partnered with the National Renewable Energy Laboratory (NREL) to accelerate the development of unique protection schemes to enhance PSCs' lifetime. Specifically, our team aims at eliminating two stress factors and technical barriers responsible for PSC degradation: 1) high temperatures during processing and 2) atmospheric effects during PV operations.

PROJECT STATUS/RESULTS: HNEI has developed a new composite integrating multi-functionalities such as *corrosion resistance*, *lightweight*, and *flexibility* as well as *tunable optoelectronics*. Unlike most conductive flexible polymers, where media are coated on top providing only *in-plane* conductivity, HNEI's transparent conductive composites (TCC) innovate by allowing simultaneous high optical transparency (%T>90% in the 370nm-2000nm region) and high *out-of-plane* electrical conductivity ($R<0.2\ \Omega.cm^2$). This unique characteristic is permitted by highly conductive 50-micron Ag-coated PMMA spheres protruding out of a transparent non-conductive polymer.

In this project, TCCs serve as gas-barrier located between the PSC and metal top contacts, providing a conformal hermetic seal repelling moisture and oxygen while preventing out-diffusion of volatile species. TCCs offer at least three main advantages over traditional "glass-glass" encapsulation. First, our composite fully cures at room temperature, which tackles the first barrier and eliminates all adverse thermal effects encountered in conventional sealant/adhesive technologies (which require curing above 100°C). Also, the protruding particles in TCC act as direct electrical access points to the underlaying structure. Therefore, the coating is not spatially restricted and can be applied directly on top of the PSC and can extend to the device edges, sealing directly the top and sides of the PV stack to the operating environment, which addresses the second barrier with no risk of lateral electrical shorting. Finally, there is no need for an extra encapsulating glass cover with TCCs, reducing module weight and cost.

Our team has demonstrated that TCCs can maintain virtually 100% of their optical and electrical properties for over 1,000 hours of outdoor exposure under Hawaiʻi's tropical semi-arid climate, while TCC-coated PSCs preserve over 90% of their initial efficiency after 1,000 hours of accelerated testing under 45% relative humidity at 50°C. Current efforts are focused on reducing TCC's water vapor and oxygen transmission rates to meet packaging standards. To date, this project has produced "**Transparent Conductive Composites—A New Class of Encapsulants for Durable Perovskite Photovoltaics**", presented at the MRS Spring 2023 meeting.

Funding Source: Department of Energy; Energy Systems Development Special Fund

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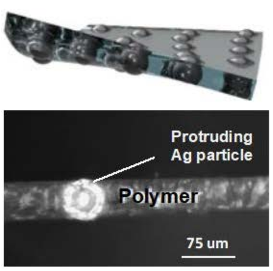
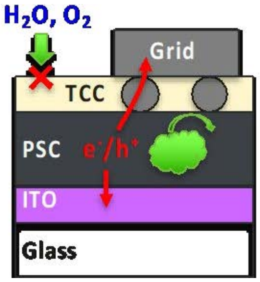
Last Updated: November 2023





G4: Develop 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 LOHCs 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 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.

In collaboration with UH's Department of Chemistry and the DOE-HyMARC Consortium (including Pacific Northwest Laboratory and National Renewable Energy Laboratory), this project targets 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 initial studies were focused on synthesis and characterization of a variety of ionic liquid borohydride LOHCs materials, as well as, carbazole and pyridine-based borohydride LOHCs. Characterization of the synthesized materials was performed using nuclear magnetic resonance spectroscopy (NMR), infrared vibrational spectroscopy (FTIR) and thermogravimetric analyses (TGA-DSC). The vibrational spectroscopy confirmed the typical borohydride peaks in the 2200-2500 cm^{-1} and 1100-1400 cm^{-1} region whilst ^{11}B solution NMR spectroscopy directly confirmed the BH_4^- ion peaks, at -36 to 39 ppm region. The dehydrogenation of the materials was performed below 200°C. Attempts to re-hydrogenate the materials in Parr Inc. high pressure reactors vessels were unsuccessful in presents and absents of Ru and Pd based catalysts.

The next phase of the project was focused on preparation and (de)hydrogenation performance studies of N-heterocycle-magnesium borohydride (LOHC-$Mg(BH_4)_2$) solutions with and without catalyst. These studies are meant to allow the identification of the optimal N-hetrocycle based LOHC-$Mg(BH_4)_2$ solutions/emulsions for development as hydrogen carriers. The N-heterocycles analyzed included (de)hydrogenated indole, methyl imidazole 1,4-bipiperidine, morpholine, butyl-imidazole, N-methylindole, 1,2 dimethy-imidazole, quinolone, and pyrrolidine.

The LOHC-$Mg(BH_4)_2$ screening reactions were performed in Parr mini-reactors at 180-200°C for up to 24 hours. Hydrogen evolution from the solutions was confirmed by the increase in pressure of the reactor vessels. Analyses of the dehydrogenated materials was performed utilizing ^{1}H and ^{11}B NMR. Products formation upon H_2 release from the LOHC-$Mg(BH_4)_2$ samples was confirmed by ^{11}B peaks at -23 to -31 ppm (cyclic B-N species) and -5 to -18 ppm

N-BH$_x$ (borane species). The best dehydrogenated $Mg(BH_4)_2$-LOHC mixtures based on NMR results and H_2 release pressure were N-heterocycles solutions containing 1,4-bipiperidine, morpholine, and pyrrolidine. The 1:6 $Mg(BH_4)_2$/pyrrolidine emulsions were found to release the most hydrogen, at 49 to 52 g H_2 /L.

The re-hydrogenation of the best N-heterocycles was performed at 180°C for up to 72 hours. The catalysts utilized in the re-hydrogenation reactions of the heterocycles-$Mg(BH_4)_2$ were Ru/C and Ru/Al_2O_3 at 5-10 wt%. However, none of the dehydrogenation products were discovered to undergo rehydrogenation back to the starting materials under hydrogen pressure of 80-120 bars.

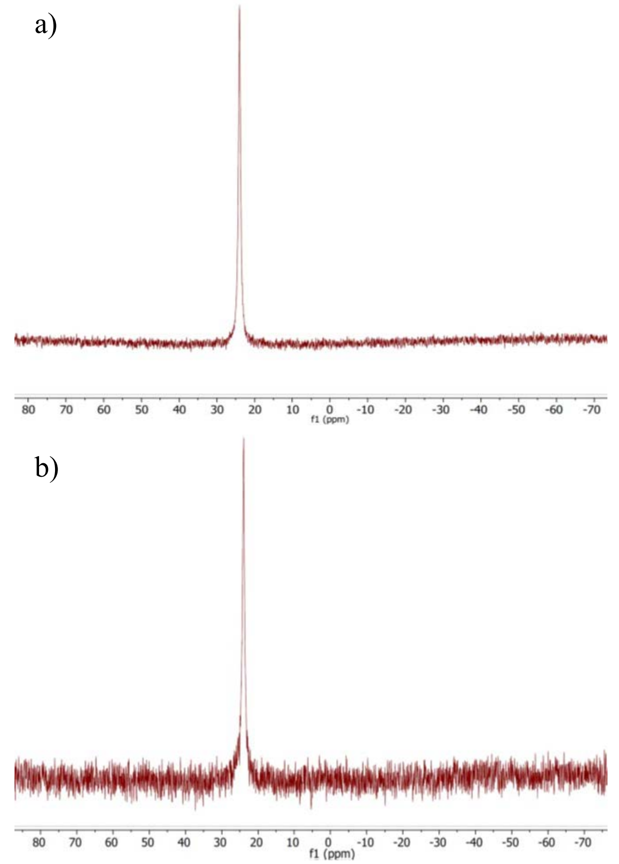


Figure 1. ^{11}B NMR of Pyrrolidine + 6 $Mg(BH_4)_2$ mixture (a) dehydrogenated at 180°C for 24 hours followed by (b) re-hydrogenation at 180°C for 72 hours.

The dehydrogenation of the $Mg(BH_4)_2$/pyrrolidine emulsions was discovered to form trispyrrolidinoborane, $B\{N(CH_2CH_2)\}_3$ complex with a peak at -23 ppm (Figure 1a). As seen in the NMR spectra (Figure 1b), there is no evidence of the reformation of the $Mg(BH_4)_2$ after re-hydrogenation of the product. The $Mg(BH_4)_2$ normally occurs as a peak with a chemical shift at ~ -41 ppm in ^{11}B NMR spectra. The re-hydrogenation back to $Mg(BH_4)_2$ or boranes is hindered by the challenge of adding hydrogen across the highly stabilized B-N bonds of the trispyrrolidinoborane.

Our future work will continue to explore the discovery of new LOHC-$Mg(BH_4)_2$ type systems which can be rehydrogenated using catalysts. However, in light of the challenges of re-hydrogenation of the LOHC-$Mg(BH_4)_2$ solutions/emulsions to borohydrides or boranes that we have studied to date, we will be exploring new alternative routes generated through this project such as the reversible (de)hydrogenation of the heterocyclic rings of trispyrrolidinoborane, (TPB) to give trispyranoborane, (TPyB) (Figure 2).

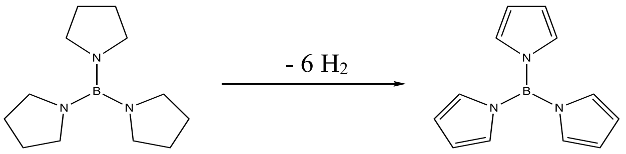


Figure 2. Dehydrogenation of trispyrrolidinoborane to trispyranoborane.

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

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Last Updated: November 2023

G5: Forward Osmosis Draw Solutions for Seawater Desalination

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to fabricate a forward osmosis (FO) system and develop novel inorganic salts and ionic liquid draw solutes for use as energy efficient, high water flux, and low toxicity draw solutions in FO 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 (RO) or FO technologies.

BACKGROUND: FO is a promising low pressure water purification technology with low electrical energy use potential that is less hindered by the drawbacks of high hydraulic pressure of RO water purification technology. The widespread commercialization of FO 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. FO 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.

PROJECT STATUS/RESULTS: Our research is focused on fabricating a precise and accurate FO water purification system, followed by development of inorganic salts and ionic liquid based draw solutes with high desalination performance that 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.

Over the last year, we finalized the benchmarking of the performance of the custom fabricated FO system using commercial draw solutes (potassium chloride and ammonium chloride) to allow for in-depth draw solutions (DS) development and evaluation. We screened the performance of various draw solutions (including potassium lactate, EMIM acetate, glucose and potassium gluconate) on the optimized FO system using DI water or seawater obtained from Ala Moana beach as feed solutions. The performance evaluation of draw solutions using seawater as feed solution, indicated relatively high-water recovery and water flux with the new draw solutions of potassium lactate and EMIM acetate ionic liquid. The non-toxicity of the potassium lactate draw solution makes it usable for multiple applications. Further work will include optimizing the potassium lactate water recovery and regeneration process.

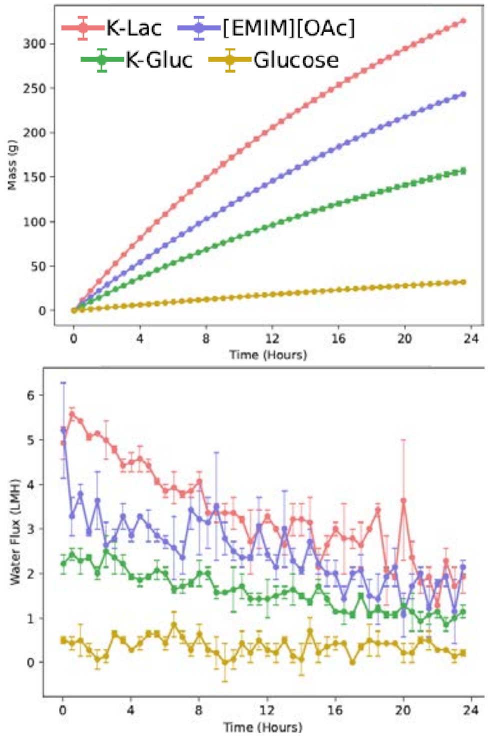

Figure 1. Mass of water recovered from Ala Moana Seawater feed solution over time (top) and the corresponding change in water flux (bottom).

Funding Source: Office of Naval Research

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Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix G: Advanced Materials

G6: UH and UW Materials Research and Education Consortium (MRE-C)

OBJECTIVE AND SIGNIFICANCE: The objective of the University of Hawaiʻi (UH) and University of Washington (UW) Partnership for Research and Education in Materials (PREM) program is to develop foundational knowledge about advanced nano-to-macroscale defect-bearing and doped materials and the properties controlling their unique behaviors, and investigate their use for future energy technologies. If successful, the project would develop the foundation necessary for increasing participation in materials science and STEM at undergraduate and later graduate level by underrepresented groups (URGs), enabling diverse student participants to perform research at the frontiers of the world's greatest materials research challenges.

BACKGROUND: This project is focused on increasing Materials Science and STEM participation by unique URGs – in particular, Native Hawaiians and Pacific Islanders (NHPI), women, and Veterans to equity – by creating a pathway that recruits and retains participants and keeps them on track towards degree attainment. The Seed PREM is configured to capitalize on synergistic expertise and exceptional resources in materials syntheses and characterization available at UH and UW to create close interdisciplinary research collaborations emphasizing the education and training of a diversified next generation of scientists and engineers.

The project research on defect-bearing and doped materials is organized into four thrusts aligned with UW's Materials Research Science and Engineering Center Interdisciplinary Research Groups (MRSEC IRGs): 1) dopant control in boron compounds for tailored gas sorption; 2) defect modeling, characterization, and engineering in ordered vacancy compound chalcopyrites for photovoltaic applications; 3) the role of hydrogen in the chemistry of proton-irradiated solids; and 4) strain control of electronic and magnetic properties of solid materials. The results of this research will lead to new materials and the understanding of new phenomena critical for solving emerging needs in energy storage and durable space technologies.

PROJECT STATUS/RESULTS: The research and education initiatives are targeted to encompass: strong student dual-mentoring by both UH and UW senior participants, annual in-person faculty/student summer research exchanges complimented by regular virtual exchanges, UH-UW co-development of teaching materials, and an annual student symposium.

Figure 1. Student presentation during 2022 summer research experience at UW.

The main focus of the last year was the retainment of students in the four research thrusts through the full realization of M.O.R.E. strategy, encompassing mentoring (M), outreach (O), materials research (R), and materials science education (E). The student research activities were focused on design and syntheses of materials and/or characterization of the materials using general lab equipment and specialized instruments. A total of 24 UH-UW exchanges have assisted with students' retainment on the partnership to date, including 8 student exchanges during this period.

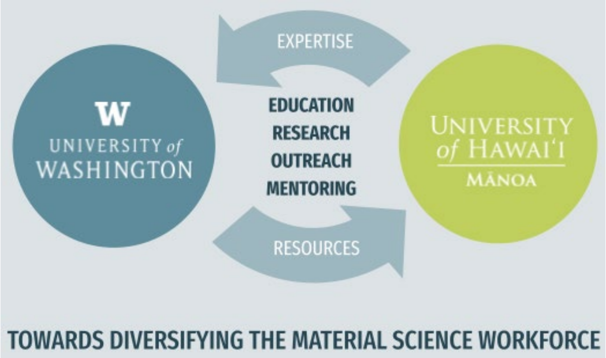

Figure 2. Strategy and goals of the PREM program.

In March 2023, a two-day MRSEC faculty exchange visit to UH occurred. The visit focused on accelerating and expanding research and education activities in the PREM thrusts. Student research presentations, informational sessions for students, and UH campus laboratory and facility tours also took place over these two days. Fifteen faculty members from UW and UH spanning seven various disciplines, along with UH's Provost, attended these meetings. During this visit, the need for location-based research and education in the PREM to solve Hawai‘i's materials challenges was seen as an important area to consider moving forward.

Figure 3. MRSEC faculty exchange visit in March 2023.

The PREM outreach efforts for building and sustaining the URG pipeline into materials science and STEM at UH continue to be based on a bottom-up strategy centered on active engagement of Hawai‘i schools to spark early interest in STEM and materials science. Hence, we expanded our outreach activities to five public schools (‘Ilima Intermediate, Kaiser High, Radford High, UH Laboratory School, and Waipahu High) to complement our continued outreach efforts to Kamehameha Schools.

Figure 4. PREM research student outreach efforts during a K-12 student visit.

Figure 5. PREM faculty and students participating at the 2023 Kamehameha Schools' science fair.

Funding Source: National Science Foundation

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Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix G: Advanced Materials

G7: Development of Novel Air Filtration Materials

OBJECTIVE AND SIGNIFICANCE: The objective of the project is the design, synthesis, and characterization of novel, reversible high-performance acidic gas (SO_x, NO_x and H_2S) contaminant absorbent materials. The materials under development would enable fuel cell vehicles to be efficiently operated under harsh atmospheric air environments. If successful, sorbents under development will assist the fuel cell filter industry and reduce environmental contamination from hazardous absorbent waste.

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

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

PROJECT STATUS/RESULTS: Nano confinement of the absorbents in highly porous materials is being performed in order to increase acidic gas-sorbent interactions and hence gas sorption performance. Nano confinement is especially critical for ionic liquids absorbents since they have high viscosity, which limit gas diffusion distances into the bulk of the material. We have physically deposited thin films of 1-ethyl-3-methyl imidazolium acetate ionic liquid onto activated carbon that remain intact during exposure to SO_2 and/or NO_2 contaminated air streams. The sorbents being developed also have relevance in other applications requiring acidic gas (SO_x, NO_x and H_2S) contaminant mitigation, including flue gas cleaning and natural gas purification.

We synthesized and characterized metal containing ionic liquids (metallo ionic liquids) containing Zn, Mg, Fe or Mn cations with general empirical formula $M_x(OAc)_y[EMIM]_z$. About 5 wt% or 10 wt% of the synthesized metallo-ionic liquids (MIL) were supported onto nano-porous coconut based activated carbon. The activated carbon-metallo ionic liquids absorbents were screened for their potential to filter elevated levels of sulfur dioxide (10 ppm in simulated air) using a custom designed and fabricated filtration materials test stand. The lab scale tests were performed at 1-2 LPM and relative humidity of 40-50%. The initial results indicate higher sulfur dioxide break through times with the Mg and Zn MIL-activated carbon absorbents (Figure 1).

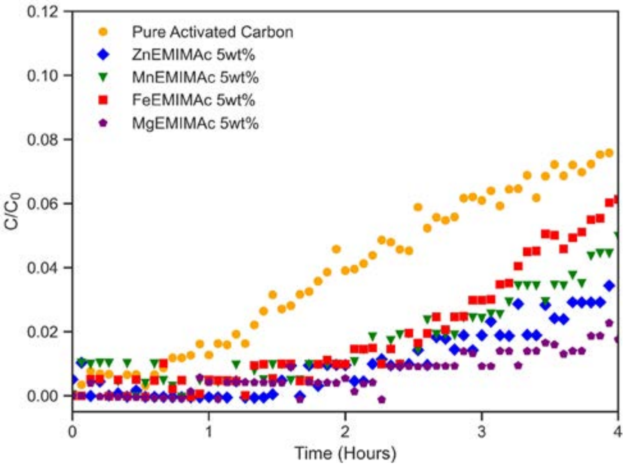

Figure 1. Comparative studies of sulfur dioxide (SO_2) breakthrough curves for 5 wt% metallo ionic liquids supported onto nano-porous activated carbon under a challenge gas of 10 ppm SO_2 with balance purified air.

Further work will involve optimizing the performance testing and integration of the developed absorbents with commercial media to form improved hybrid multiple gas contaminant filter media with higher breakthrough filtration performance under harsh environments with elevated levels of gas contaminants.

Funding Source: Office of Naval Research

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Last Updated: November 2023

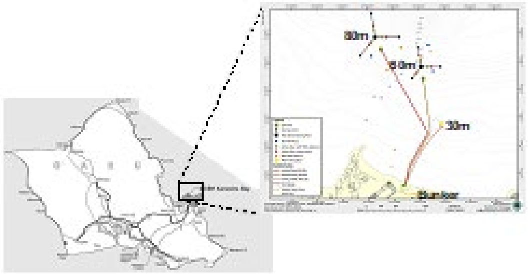
Hawaiʻi Natural Energy Institute Research Highlights

Appendix H: Ocean Energy

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

<u>OBJECTIVE AND SIGNIFICANCE</u>: Wave energy has the potential to address global renewable energy goals, yet it poses daunting challenges related to commercializing technologies that must produce cost-competitive electricity while surviving an 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.



<u>BACKGROUND</u>: 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. 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 $6M 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 includes: 1) examining 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, environmental/environmental sensing, and navigation; 2) design of an AUV docking/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 and AUV recharge; 4) advancement of a novel breakwater system with integrated OWC power generation; and 5) concept development of a floating flap-type WEC.

In Summer 2022, an additional $3.6M was awarded by Navy to further extend core support to WETS, including key infrastructure upgrades/maintenance.

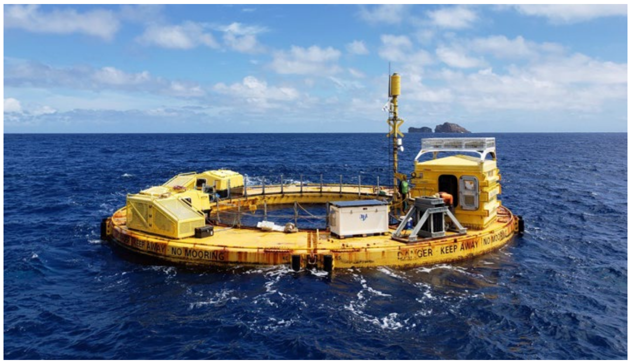
<u>PROJECT STATUS/RESULTS</u>: Since mid-2015, the following major activities have occurred at WETS, with HNEI in both supporting and leading roles:

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

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

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

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



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

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

Issues stemming from COVID, funding, and technical challenges have substantially delayed planned WEC deployments over the past few years, but three deployments are currently happening, or 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. New anchors were deployed at the WETS 30m berth in support of this project, with work complete in August 2022, and a new electrical/data junction box was installed in

September 2023. The latest expectation for deployment of the device is late fall 2023.

2. Deployment of the C-Power SeaRay WEC. This is a stand-alone (not grid-connected) deployment of a small, 1kW device that will feed power to a subsea acoustic sensing system from Biosonics, as well as other environmental sensors. The device was deployed at WETS in early October 2023, but suffered some early damage and will need to be redeployed at a future date.

3. Deployment of the Ocean Energy (Ireland) OE35 WEC at the 60m berth. This device has been in Hawaiʻi since December 2019, and underwent drydock repairs in Aug/Sep 2022, after extensive delays. It is currently undergoing replacement of key electrical components, and final testing, and should be ready for deployment to WETS in late 2023 or early 2024.

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

Contact: Patrick Cross, pscross@hawaii.edu

Last Updated: November 2023

H2: The Hawaiʻi Wave Surge Energy Converter (HAWSEC)

OBJECTIVE AND SIGNIFICANCE: The objective of the Hawaiʻi Wave Surge Energy Converter (HAWSEC) project, funded primarily by the U.S. Department of Energy (DOE), is to mature a wave energy converter (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 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 expertise related to WEC design.

The HAWSEC concept is based on the oscillating wave surge 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. The small-scale version of the flap is shown in Figure 1.

We are exploring 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.

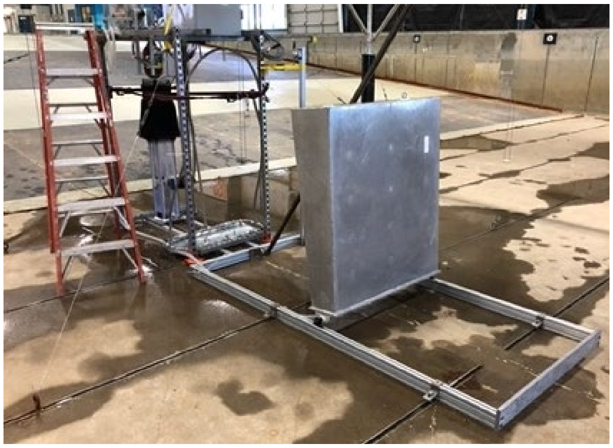


Figure 1. HNEI's HAWSEC system in Oregon State University's wave basin for testing.

PROJECT STATUS/RESULTS: This project was initated in August 2020. 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.

To date, Tasks 1 through 4 above are now complete. The smaller-scale flap system, including the flap itself and both versions of the hydraulic power takeoff (PTO) system, was designed and fabricated in 2021 and early 2022. A hydraulic bench test setup was completed in our lab on the UH campus in early 2022, including a linear actuation system that is capable of simulating realistic wave forcing. Lab testing was carried out between January and May 2022, resulting in readiness to ship the full system to Oregon for wave basin testing at OSU.

Nearshore testing of the flap in local waters at Makai Research Pier was conducted in May 2022 (Figure 2), with encouraging results that further de-risked the upcoming basin tests.

Figure 2. Flap testing at the Makai Research Pier.

Controlled wave basin testing at OSU was completed in two phases, without and with a power takeoff (hydraulic) system, in June and October/November 2022 (Figure 3). Excellent results were obtained, particularly for the high-head PTO, where the power produced exceeded expectations. Due to this, the high-head PTO – in which a hydraulic cylinder pumps water at high pressure through a nozzle to rotate a Pelton wheel turbine – is the selected approach for the second phase of the project, where the device will be scaled up in size with the goal of conducting subsequent testing and validation.

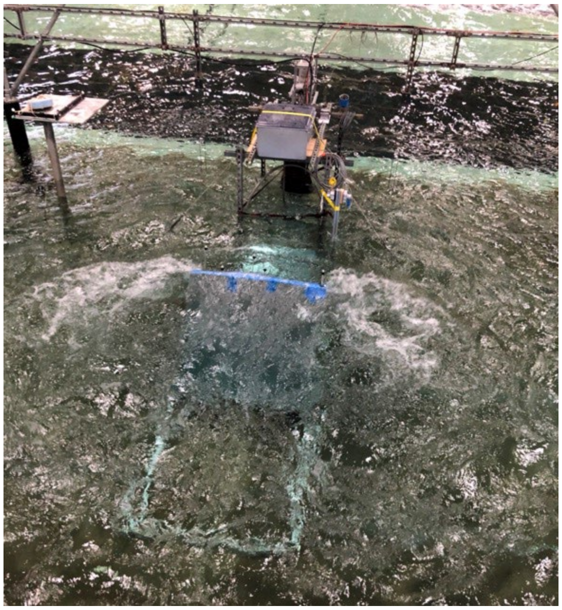


Figure 3. Controlled wave basin testing at OSU.

A Go/No-Go decision process with DOE will be undertaken in February/March 2024, and the project is expected to reach completion in the spring of 2025. This extended timeline stems from substantial procurement challenges in Budget Period 1 and a shipping-related setback, which cost the project several months. Despite these delays, the project is meeting its technical objectives and has resulted in a WEC concept that is of high interest to DOE and to our partners at the National Renewable Energy Lab, who are now working with us to initiate a new project that will utilize our small-scale flap for a PTO development of their own and subsequent deployment at Makai Pier.

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

Contact: Patrick Cross, pscross@hawaii.edu

Last Updated: November 2023

I1: Asia Pacific Regional Energy System Assessment (APRESA)

OBJECTIVE AND SIGNIFICANCE: In August 2017, HNEI was awarded a grant from the Office of Naval Research (ONR) to support energy system transitions in select locations throughout the Asia-Pacific region under the Asia Pacific Regional Energy System Assessment (APRESA) program. The objective of APRESA is to develop comprehensive energy system assessments in the Asia-Pacific region regarding energy transition strategy, policy, regulation, technology options, demonstrations, implementation plans, and training based on the specific requirements or needs of the targeted jurisdictions and strategic alliances.

BACKGROUND: During the six years of APRESA activities, HNEI established substantive strategic partnerships with national, regional, and local jurisdictions, as well as private and public stakeholders including numerous utilities, universities, and other research and international aid and development entities, such as the World Bank (WB), Asian Development Bank (ADB), Australian Infrastructure Financing Facility for the Pacific (AIFFP), The Asia Foundation (TAF), The Maureen and Mike Mansfield Foundation (TMF), U.S. Agency for International Development (USAID), and U.S. Department of Defense (DOD) organizations in the areas of interest. Based on the programmatic success of these strategic partnerships, ONR has extended the APRESA program for an additional two years through 2024.

Nations with ongoing active engagement and support activities include Vietnam, Thailand, Laos, Indonesia, Papua New Guinea, and the Philippines. New engagements with Pacific Island countries (PIC) include Palau, Cook Islands, the Republic of the Marshall Islands, and the Commonwealth of the Northern Mariana Islands. The criteria for selection of jurisdictions include: 1) those with significant rates of projected demand growth requiring rapid energy system expansion and transformation, 2) strategic trade and geopolitical opportunities to the United States, 3) potential to integrate renewable energy technologies, and 4) a collaborative environment to conduct the work.

In addition to the deep local partnerships formed in these jurisdictions, this program has led to a highly 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, Chemonics, and Delphos International).

USAID partner country governments need 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, promotes 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 its 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 is using the remaining APRESA funding to extend the efforts in the current countries and to expand this work to other countries, regions, and DOD facilities of interest, with particular focus on PICs. These efforts are supported by a number of HNEI faculty and staff, including those of the HNEI's Grid*START* team focused on advanced grid technologies and enabling policy and regulation.

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 in this Appendix.

Innovation System Mapping Project in the Renewable Energy Sector in Vietnam
Under this effort, HNEI provided financial support and guidance, to the National Institute for Science and Technology Policy and Strategy Studies (NISTPASS) to map the innovation opportunities associated with renewable energy (RE) sector development in Vietnam. While the development of renewable energy resources in Vietnam is a government priority, there has been a lack of clarity about the role of many organizations in Vietnam impacting energy development, the relationship between them, and the policies required to foster energy innovation. An objective of this work was to identify which Vietnamese stakeholders in the RE sector would benefit from further policy and institutional support. To meet the aggressive government goals associated with RE innovation, the project is also focused on identifying relevant organizations in the sector and understanding how they interact with each other and as a system.

In April 2023, NISTPASS held a workshop with various Vietnamese groups titled "Mapping Sector Innovation System of Renewable Energy in Vietnam," which was attended by HNEI and ONR personnel. Incorporating inputs from this workshop, NISTPASS submitted a book titled "Sectoral Innovation System in Renewable Energy: Case of Solar and Wind in Vietnam." This project is completed, but HNEI has initiated discussions for a small, follow-on planning award to continue work in this area.

Saigon Energy Hub (SEHub) Support
HNEI is collaborating with Ho Chi Minh City's Institute for Regional and Urban Studies (IRUS) to develop a public renewable demonstration and technology center to raise the community awareness of the needs, the feasibility, and the benefits of energy efficiency and renewable energy. Originally planned for an outdoor public park venue, the project now consists of a number of energy efficiency and renewable energy themed workshops to be conducted at new facilities located at Ho Chi Minh City Union of Science and Technology Association's Headquarters. A Pre-Feasibility report was submitted by IRUS, identifying the site, the partners, projected activities, space utilization, equipment and furnishings, timeline and budget, and financing sources.

In September 2023, UH and IRUS personnel met to discuss progress and the upcoming energy-efficient and renewable energy themed workshops, which will continue through July 2024. This work is described in more detail in Appendix I2.

Provincial Electricity Authority of Thailand (PEA) Collaboration
HNEI has developed a capacity-building program focused on topics of renewable energy grid integration, smart grid technologies, microgrid assessment and design, and the development of advanced EV charging applications for engineers from the Provincial Electricity Authority of Thailand (PEA). PEA is a large Thai distribution grid operator with a service territory spanning all of Thailand, except for the Bangkok metropolis and two adjoining provinces (Thailand has 77 total provinces).

Since Spring 2020, HNEI Grid*START* has delivered a training program for PEA select engineers. The program accommodates two classes of six engineering interns each year. The program lasts for twelve weeks and includes 40 hours of lectures and team-oriented deep immersion in custom "hands-on mini-project" research, development, and test endeavors tailored to the learning needs of working utility engineers focused on energy distribution systems. Due to COVID-19 travel restrictions, the PEA intern program experienced delays and shifted partially to online learning in 2020-2021. In 2022, with the lifting of travel restrictions, two classes of PEA interns were trained at HNEI in two separate sessions. Each class was divided into sub-groups working on various mini-projects, which included optimizing virtual power plant dispatch and demand response, improving electric vehicle (EV) energy consumption estimation, assessing PV hosting capacity, and designing optimized microgrid systems.

While HNEI Grid*START* completed the development of the class curriculum and a mini-project research plan focused on microgrid design and operation, travel to Hawaiʻi by the incoming 2023 PEA intern classes was unexpectedly suspended due to unforeseen circumstances amid the ongoing repercussions and political conditions in Thailand following the contested results of the 2023 national elections. It is anticipated that the PEA intern training at HNEI will resume in 2024. This work is described in more detail in Appendix I3.

Waste-to-Bioenergy Conversion for Community PV-BioGrid
With APRESA funding, HNEI contracted Chiang Mai Rajabhat University, Thailand to conduct an assessment of small biomass systems as a firm power option in islanded settings. The study included 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 the results, an anaerobic digestion system was selected to integrate into a grid-isolated community dependent largely on PV for electricity. The system has been installed at the University and shake down testing has begun.

Sustainable Aviation Fuel (SAF) Production
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.

Additionally, APRESA funding contributed to a sustainable aviation fuel workshop in Bangkok, Thailand in May 2023, which was organized by the Federal Aviation Administration (FAA), the U.S. Trade Development Agency, Energy Technology Center of Thailand, and HNEI. Its goal was to share information on SAF developments in the region and to identify barriers to implementing SAF value chains spanning feedstock production to end use. Participants from various Asia-Pacific countries attended, representing civil aviation authorities, government policymakers, airlines, SAF feedstock producers, consumers, and technology providers, university researchers, and airport operators jet fuels and limited opportunity for electrification.

Support to the USAID Energy Secure Philippines (ESP) Program
In 2019, HNEI Grid*START* collaborated with USAID Clean Power Asia to provide technical and capacity building support to the Philippines Department of Energy (PDOE) for the preparation and presentation of its Department Circular regarding the development and implementation of net energy metering (NEM) programs. HNEI Grid*START* continues to support the Philippines' power sector by delivering both collaborative (APRESA funded) and USAID Energy Secure Philippines (ESP) program funded technical support to the Philippines Energy Regulatory Commission (ERC), distribution utilities (DUs), and other relevant agencies. Specifically, HNEI Grid*START* has been assisting them in developing a comprehensive set of rules for an "off-grid" NEM program tailored to small, rural area grid systems in the Philippines. HNEI Grid*START* is also collaborating with USAID ESP and the ERC to establish a BESS regulatory framework for the Philippines.

In Summer 2022, HNEI Grid*START* submitted reports and documentation on NEM rules for isolated "off-grid" island systems and a BESS regulatory framework in the Philippines to USAID ESP and the ERC. The reports were presented in person in Manila in August 2022, followed by a workshop with the USAID ESP and the ERC in September 2022 to draft BESS regulations for the ERC to promulgate.

In February 2023, HNEI Grid*START* conducted a second in-person writing workshop on the ERC's draft BESS regulation. In June 2023, HNEI Grid*START* provided capacity building on microgrids to the ERC and power system resiliency to the DOE. In November 2023, HNEI Grid*START* delivered in-person capacity building on power system resiliency to the PDOE to assist DUs. HNEI is also working with USAID ESP to develop and administer a hybrid classroom/hands-on training curriculum to help off-grid DUs optimize NEM uptake, which is planned for delivery in the first half of 2024. This work is described in more detail in Appendix I5.

USAID Sustainable Energy for Indonesia's Advancing Resilience (SINAR) Program

The USAID's Sustainable Energy for Indonesia's Advancing Resilience (SINAR) program is a five-year initiative to support Indonesia's transition to a clean energy economy. HNEI Grid*START* is providing technical support to the program by helping to build capacity on a range of topics related to advanced energy systems, including financing, procurement, planning, and operations. HNEI Grid*START*'s work is also focused on improving the performance of energy utilities, such as PT Perusahaan Listrik Negara (PLN, or State Electricity Company) and strengthening the institutional framework and capacity of the energy sector. This includes helping to develop and implement competitive procurement standards, improve cost recovery mechanisms, and modernize planning and operating practices.

In February 2022, HNEI Grid*START* shared Hawai‘i's renewable energy transformation experience with Indonesia's Directorate General of Electricity and Ministry of Energy and Mineral Resources in a three-day webinar. Following the webinar, in May 2023, HNEI was invited and traveled to Indonesia and conducted a three-day workshop on small island grid planning for PLN in Bali, as well as a one-day webinar for the SetjenDEN (the National Energy Council of Indonesia) in Jakarta. Discussions with Indonesian stakeholders during that trip have led to ongoing discussions regarding additional capacity building in Hawai‘i, which is planned for 2024. This project is described in more detail in Appendix I6.

Électricité du Laos (EDL) and Ministry of Energy and Mines (MEM) Support

HNEI has agreed, pursuant to an October 25, 2021 Letter of Engagement with EDL, to deliver needed technical capacity building support at EDL's request on the following topics: 1) practical guidance for interconnection of distributed solar PV systems to the distribution grid; 2) training curriculum on topics such as voltage regulation and variation, frequency limits, voltage dips, voltage unbalance, voltage flicker and harmonics; and 3) standards of practice for installing and operating underground distribution cables. With the lifting of COVID-19 travel restrictions by the Laos government, plans are underway for HNEI to deliver in-person and remote training on these topics starting in 2024.

USAID Southeast Asia's Smart Power Program (SPP) – Laos

A Letter of Collaboration, initiated by Deloitte Consulting (Deloitte), the prime contractor for the USAID Southeast Asia Smart Power Program (SPP), was signed with HNEI on October 27, 2022. The USAID SPP is a $40 million, five-year initiative with the goal of mobilizing $2 billion in blended financing for clean energy infrastructure. The program sets out to drive economic growth and development of Southeast Asia, focusing on creating secure, market-oriented, and environmentally responsible energy sectors. The ultimate vision is to help the region achieve its target of net-zero greenhouse gas emissions by 2050.

Among the initial tasks outlined in the collaboration agreement, HNEI is providing support to Électricité du Laos (EDL) and the Lao Ministry of Energy and Mines (MEM) focused on enhancing power system resilience, implementing demand-side management/demand response (DSM/DR) strategies, and integrating variable renewable energy (VRE) resources into their transmission and distribution systems.

In 2023, HNEI Grid*START* delivered updated Feasibility Study Guidelines for wind, solar, and biomass energy projects in Laos. Grid*START* also provided an updated Grid Code for Laos that incorporates interconnection standards for inverter-based resources as well as updated interconnection standards for PV systems connected at the distribution level. In addition, HNEI Grid*START* conducted two capacity building sessions for EDL and MEM staff focusing on the updated Grid Code and distribution interconnection standards. This work is described in more detail in Appendix I7.

Production Cost Estimates for Millettia pinnata

Millettia pinnata, also called karanja or pongamia, is indigenous to the Indian subcontinent and Southeast Asia. This leguminous tree bears seed rich in fatty acids (27 to 39 wt%) that when harvested can be processed into oil, nitrogen-rich meal, and lignocellulosic pod fractions that all can play roles in improving the resiliency in both food and energy for island communities in tropics. APRESA funds support an initial cost of production analysis to determine farm gate prices for harvested seed pods based on costs to establishment, maintenance, and harvesting costs for pongamia orchards in Hawai‘i. This analysis framework can be extended to other locations in the tropical Pacific.

Energy Systems Regulatory and Technical Support for Pacific Island Countries

HNEI Grid*START* is providing technical and regulatory/policy support to various Pacific Island Countries (PIC), such as the Republic of Palau (Palau), Cook Islands, Commonwealth of the Northern Mariana Islands (CNMI), and Republic of the Marshall Islands (RMI).

In September 2023, HNEI Grid*START* hosted two trainings for PIC representatives in Hawai‘i: a three-day training program for the newly appointed Director of Palau’s Energy and Water Administration (PEWA) and utility staff on a variety of energy transition policies and regulations, and a one-day training program for the members of the Cook Islands’ power company, Te Aponga Uira (TAU), including Board members, the Chief Executive Officer, and the Chief Engineer. Topics included Hawai‘i’s energy transition, grid modernization, battery energy storage systems, and a case study on Moloka‘i’s distributed PV integration. Discussions with TAU are ongoing to define further HNEI support across a wide range of energy and regulatory needs.

At the Pacific Power Association’s (PPA) 30th Annual Conference in Saipan, HNEI Grid*START* met with a CNMI’s Commonwealth Utilities Corporation (CUC) Board member who expressed interest in HNEI’s support for their renewable integration plans. Follow-up meetings with CUC will be scheduled to identify and prioritize areas of support. Grid*START* also met with representatives from RMI’s National Energy Office during the conference, which requested HNEI to review and comment on RMI’s new energy legislation and regulations. Based in part on interactions with other stakeholders at the PPA conference, HNEI Grid*START* is further engaged in discussions to support additional projects in Samoa, Tonga, the Federated States of Micronesia, Nauru, Kiribati, Tuvalu, and Niue. This work is described in more detail in Appendix I8.

Funding Source: Office of Naval Research

Contact: Richard Rocheleau, rochelea@hawaii.edu;
Leon Roose, lroose@hawaii.edu;
Scott Turn, sturn@hawaii.edu;

Last Updated: November 2023

I2: Saigon Energy Hub (SEHub) Support

OBJECTIVE AND SIGNIFICANCE: HNEI is collaborating with Ho Chi Minh City's Institute for Regional and Urban Studies (IRUS) to develop a public renewable demonstration and technology center to raise the community awareness of the needs, the feasibility, and the benefits of energy efficiency (EE) and renewable energy (RE). In addition to raising community awareness, the project is intended to strengthen the role of social media in the engagement of policy makers and the private sector.

This project will comprise two phases: a planning, design, and construction phase for development of the workshop platform and an implementation phase where contractors shall present eight (8) publicly accessible energy-related workshops through the workshop platforms.

BACKGROUND: Included among the objectives of the Hawaiʻi Natural Energy Institute's Asia Pacific Regional Energy System Assessment (APRESA) award from the Office of Naval Research, is to develop partnerships with national, regional, or local jurisdictions, private and public stakeholders, including universities and other research organizations in the Asia-Pacific region to enhance the reliability, stability, and resilience of the energy systems.

Under this agreement, HNEI is supporting Ho Chi Minh City's local non-governmental organization, IRUS to design and implement the Saigon Energy Hub (SEHub), a virtual, publicly accessible, education platform offering energy-related forums to the community.

PROJECT STATUS/RESULTS: The SEHub began in 2022 as a conceptual project with IRUS, defining project benefits and financial requirements in order to develop a project prospectus for future collaborative partners, including developers, financial entities, and the local government.

As the project implementer, IRUS is consolidating a local public-private partnership to support the development of the SEHub. Originally planned for an outdoor public park venue, the project now consists of a number of energy efficiency and renewable energy themed workshops to be conducted at new facilities located at Ho Chi Minh City Union of Science and Technology Association's Headquarters, at 224 Dien Bien Phu Street, Vo Thi Sau Ward, District 3 in the historical centre of Ho Chi Minh City. IRUS is completing the outfitting two meeting spaces with the equipment and technologies to present both online and offline workshops.

Figure 1. HCM-USTA Building, Ho Chi Minh City.

The workshop series will consist of eight (8) live and online energy-related workshops. IRUS will develop and present for approval the eight course topics, the course descriptions, length, and structure, timelines, target audience, anticipated participants, methods for outreach and marketing, and methods to deliver online and record workshops to make them publicly available in the future.

A Pre-Feasibility report was submitted by IRUS, identifying the site, the partners, projected activities, space utilization, equipment and furnishings, timeline and budget, and financing sources. In September 2023, UH and IRUS personnel met to discuss progress and the upcoming energy themed workshops. The project will continue through July 2024.

Funding Source: Office of Naval Research

Contact: Richard Rocheleau, rochelea@hawaii.edu

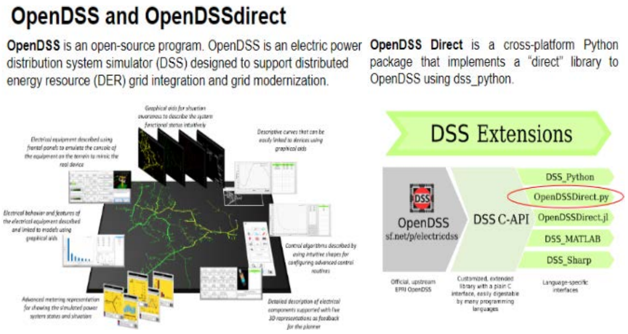
Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix I: International

I3: 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 topics of renewable energy grid integration, smart grid technologies, microgrid assessment and design, and development of advanced electric vehicle (EV) charging applications for engineers from the Provincial Electricity Authority of Thailand (PEA). The PEA is the distribution grid operator with a service territory spanning all of Thailand, except for the Bangkok metropolis and two adjoining provinces (Thailand has 77 total provinces).



OpenDSS and OpenDSSdirect

OpenDSS is an open-source program. OpenDSS is an electric power distribution system simulator (DSS) designed to support distributed energy resource (DER) grid integration and grid modernization.

OpenDSS Direct is a cross-platform Python package that implements a "direct" library to OpenDSS using dss_python.

Figure 1. Sample of the teaching materials.

BACKGROUND: Since Spring 2020, HNEI Grid*START* has conducted a training program for select PEA engineering interns. This program accommodates two classes of six engineering interns each year. The program lasts for twelve weeks, includes 40 hours of classroom-based lectures tailored to working utility engineers, and is centered on customized hands-on mini-projects focused on energy distribution systems. The lectures cover subjects such as renewable energy integration and smart grid technologies, while the mini-projects involve tasks such as developing controls for EV chargers, analyzing PV hosting capacity, studying virtual power plant (VPP) energy management, and optimizing microgrid design and operation.

PROJECT STATUS/RESULTS: Due to COVID-19 travel restrictions, the PEA intern program experienced delays and shifted partially to online learning in 2020-2021. In 2022, with the lifting of travel restrictions, two classes of PEA interns were trained at HNEI in two separate sessions. Each class was divided into sub-groups working on various mini-projects, which included optimizing VPP dispatch and demand response, improving EV energy consumption estimation, assessing PV hosting capacity, and designing optimized microgrid systems. The program is designed to substantially enhance PEA engineers' knowledge of distributed energy resource technologies, EV applications, and microgrids.

In the mini-projects for the 2022 intern classes, PEA engineers worked on economic dispatch for customer-sited PV and battery energy storage systems, enhancing EV energy consumption estimation algorithms, determining PV hosting capacity for distribution circuits, and assessing the feasibility of prospective microgrid sites in Thailand using the XENDEE modeling platform. The projects delivered deep hands-on experience and drew heavily on HNEI Grid*START*'s research, development, and testing expertise in the areas of distributed energy resources, advanced EV charging applications, and smart grid technology.

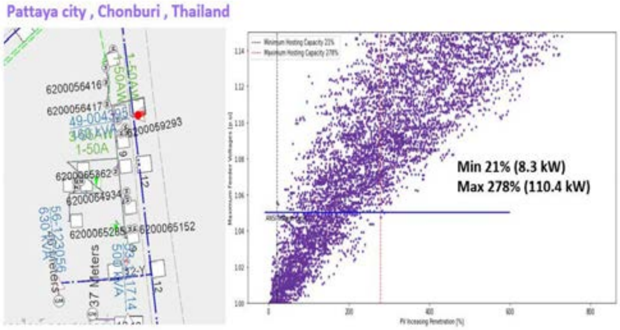


Figure 2. PV hosting capacity simulation on a PEA distribution feeder.

While the class curriculum and a mini-project focused on microgrid design and operation were developed for the incoming 2023 PEA intern classes, the PEA unexpectedly suspended travel to Hawaiʻi due to unforeseen circumstances amid the ongoing repercussions and political conditions in Thailand following the contested results of the 2023 national elections. It is anticipated that the PEA intern training at HNEI will resume in 2024.

Funding Source: Office of Naval Research

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Last Updated: November 2023

I4: USAID Papua New Guinea Electrification Partnership (PEP) Activity

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

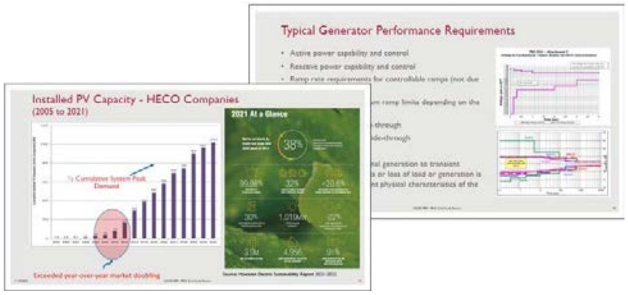
BACKGROUND: The $57 million USAID-PEP program was launched in November 2020. HNEI Grid*START* is supporting RTI in improving PNG Power Limited's (PPL) financial viability, developing off-grid electrification models, and improving PNG's energy regulations. Specifically, HNEI Grid*START* is supporting RTI on an end-to-end utility transformation of PPL by: 1) improving competitive procurement and conducting due diligence on the existing independent power producer pipeline; 2) developing viable off-grid electrification models by developing a private sector engagement strategy; 3) building a portfolio of viable sites; participating in stakeholder groups; and 4) demonstrating measurable improvement in PNG's energy regulator, the National Energy Authority (NEA), by improving the national regulatory framework for off-grid electrification and engaging stakeholders to inform and implement enabling policies and regulations.

Figure 1. PPL's Main Power Systems, extracted from the PPL Diagnostic Assessment Report submitted in 2022.

PROJECT STATUS/RESULTS: HNEI Grid*START* has been providing extensive support to the USAID-PEP program by reviewing the draft PNG Off-Grid Regulation, evaluating IEC standards for rural electrification by PNG's National Institute of Standards and Industrial Technology (NISIT), participating in stakeholder meetings, and conducting training on HOMER software. HNEI Grid*START* also reviewed updates to PNG's Third-Party Access (TPA) Code, Electricity Industry Regulations, and Grid Code for transmission-level interconnections, as well as proposing interconnection standards for inverter-based resources connected at the distribution level.

Subsequently, HNEI prepared and delivered a four-day in-person workshop in November 2022, focusing on the PNG Grid Code and distributed energy resource (DER) interconnections, PNG TPA Code and technical regulations, and public consultation with NEA, PPL, and independent power producers (IPPs). Based on additional input from RTI (i.e., the Wiring Rules), the team provided updates to the four previously reviewed Electricity Industry Regulations. Additionally, the team initiated the development of draft Distributed Generation Unit (DGU) Interconnection Standards Technical Requirements for PNG and reviewed and/or drafted ten District Energy Plan Assistance reports in support of rural electrification objectives.

In May 2023, HNEI Grid*START* collaborated with USAID-PEP on the conceptual formulation of an off-grid code for PNG. In October 2023, HNEI also provided a briefing on the Grid Code and TPA Code for presentation to the NEA Board of Directors, including a newly added section on Distributed Generating Unit Interconnection Standards Technical Requirements.


Typical Generator Performance Requirements

- Active power capability and control
- Reactive power capability and control

Installed PV Capacity - HECO Companies (2005 to 2021)

2021 At a Glance

Figure 2. Sample slides from the four-day workshop in November 2022.

Funding Source: USAID-PEP

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

I5: Support to the USAID Energy Secure Philippines (ESP) Program

OBJECTIVE AND SIGNIFICANCE: HNEI Grid*START* is delivering technical support to the USAID-funded Energy Secure Philippines (ESP) Program, the Philippines Energy Regulatory Commission (ERC), and the Philippines Department of Energy (PDOE) in their mission to advance inclusive economic growth and resilient energy sector development. This support includes the establishment of net energy metering (NEM) rules for numerous small island grid systems and the development of a regulatory framework for battery energy storage systems (BESS) adoption in the Philippines.

BACKGROUND: In 2019, HNEI Grid*START* collaborated with USAID Clean Power Asia to provide technical and capacity building support to the PDOE for the preparation and presentation of its Department Circular (DC) titled "*Promulgating Policies to Enhance Customers' Participation in the Philippines' Net-Metering Framework.*"

HNEI Grid*START* continues to support the Philippines' power sector by delivering both collaborative (APRESA-funded) and USAID ESP-funded technical support to the ERC, PDOE, distribution utilities (DUs), and other Philippine energy industry stakeholders. Specifically, HNEI Grid*START* has assisted in developing a comprehensive set of rules for a NEM program, as well as a mandated regulatory framework for BESS in the Philippines. The BESS framework includes: streamlined rules for BESS interconnection, guidelines for BESS technical codes and standards, mechanisms for cost recovery related to utility-owned BESS, and third-party-owned BESS delivering ancillary services. This work is assisting the ERC in fulfilling its mandate set by the PDOE.

PROJECT STATUS/RESULTS: In the summer of 2022, HNEI Grid*START* submitted reports and documentation on NEM rules for isolated "off-grid" island systems and a BESS regulatory framework in the Philippines to USAID ESP and the ERC. These reports were presented in person in Manila in August 2022 and a workshop with the USAID ESP and the ERC followed in September 2022 to draft BESS regulations for ERC promulgation. In February 2023, HNEI Grid*START* conducted a second in-person writing workshop on the ERC's draft BESS regulation.

Figure 1. HNEI's Philippines BESS Regulation Drafting Workshop #2 in Pasig City in February 2023.

In June 2023, HNEI Grid*START* delivered in-person capacity building on microgrids to the ERC and on power system resiliency to the PDOE. Following these presentations, HNEI Grid*START* participated as an online presenter in the Philippines' 2023 Energy Resiliency Forum at the PDOE's request.

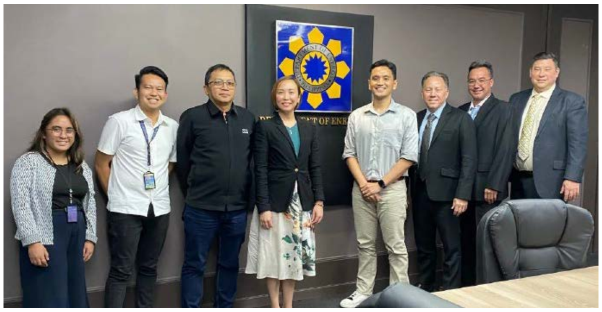


Figure 2. HNEI's meeting with the PDOE in June 2023.

In November 2023, HNEI Grid*START* delivered two days of in-person capacity building activities on energy storage systems (ESS) to the PDOE, aimed to assist DUs by: 1) providing a better understanding of the costs and benefits of ESS; 2) building an understanding of BESS behind-the-meter applications; 3) helping policymakers and regulators to address BESS-related policy and regulatory gaps; and 4) assessing the need to enhance the existing institutional approach to promote and utilize BESS in the Philippines.

HNEI Grid*START* is also working with USAID ESP to develop and administer a hybrid classroom/hands-on training curriculum aimed at helping off-grid DUs optimize NEM uptake, which is currently planned to be delivered in the first half of 2024.

Funding Source: USAID ESP Program; Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

I6: USAID Sustainable Energy for Indonesia’s Advancing Resilience Program

OBJECTIVE AND SIGNIFICANCE: In September 2021, HNEI Grid*START* was contracted by Tetra Tech ES to provide technical support for USAID’s Sustainable Energy for Indonesia’s Advancing Resilience (SINAR) program. The SINAR program aims to advance Indonesia’s development goals in expanding reliable and equitable energy services necessary for sustainable development and inclusive economic growth. SINAR program objectives include: 1) accelerating deployment of advanced energy; 2) improving performance of energy utilities; 3) adopting transparent and best value procurement; and 4) strengthening the institutional framework and capacity of the energy sector.

BACKGROUND: Although Indonesia has abundant renewable energy (RE) resources, they are not being utilized to their full potential. One of the obstacles to accelerating the adoption of RE resources is the limited experience of key energy stakeholders on proper and prudent RE planning for energy transition in accordance with local conditions and current energy policies. In an effort to help the Government of Indonesia increase the use of RE, in line with its National Energy Policy and Nationally Determined Contributions (NDC) under the Paris Agreement, USAID SINAR identified a need for Indonesia’s Ministry of Energy and Mineral Resources (MEMR) and PT Perusahaan Listrik Negara (PLN or ‘State Electricity Company’) to have a clear strategy, standard framework, and program roadmap for the successful energy transition toward net zero emissions.

PROJECT STATUS/RESULTS: HNEI Grid*START* is supporting the USAID SINAR program by providing capacity building on: 1) advanced energy systems finance and development, 2) utility cost recovery and modernization, 3) competitive procurement and domestic resource utilization, and 4) stakeholder coordination and policy improvement.

In February 2022, HNEI Grid*START* presented a three-day webinar to Indonesia’s Directorate General of Electricity (DGE) and MEMR on Hawaiʻi’s renewable energy transformation, lessons learned from incorporating increasing levels of RE, and technical issues posed by high renewable penetrations in modern power systems. HNEI’s deep knowledge and understanding of Hawaiʻi’s successful energy transformation and lessons learned garner great interest and attention not only from Indonesia but also from numerous countries in the Asia-Pacific region, due to their similar geographical and climatic characteristics.

Following the webinar, in May 2023, HNEI Grid*START* was invited and traveled to Indonesia to conduct a three-day workshop on small island grid planning for PLN in Bali and a one-day webinar for the Setjen DEN (the National Energy Council of Indonesia) in Jakarta. Discussions with Indonesian stakeholders during that trip have led to ongoing scoping discussions for additional capacity building located in Hawaiʻi, which is planned for 2024.

Figure 1. HNEI Grid*START* participants in a focus group discussion in Indonesia in May 2023.

Funding Source: USAID SINAR Program; Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

Hawaiʻi Natural Energy Institute Research Highlights

Appendix I: International

I7: USAID Southeast Asia's Smart Power Program – Laos

OBJECTIVE AND SIGNIFICANCE: A Letter of Collaboration, initiated by Deloitte Consulting (Deloitte), the prime contractor for the USAID Southeast Asia Smart Power Program (SPP), was signed with HNEI on October 27, 2022. The USAID SPP is a $40 million, five-year initiative with the goal of mobilizing $2 billion in blended financing for clean energy infrastructure. The program sets out to drive economic growth and development in Southeast Asia, focusing on creating secure, market-oriented, and environmentally responsible energy sectors. The ultimate vision is to help the region achieve its target of net-zero greenhouse gas emissions by 2050.

Among the initial tasks outlined in the collaboration agreement, HNEI is providing support to Électricité du Laos (EDL) and the Lao Ministry of Energy and Mines (MEM) focused on enhancing power system resilience, implementing demand-side management/demand response (DSM/DR) strategies, and integrating variable renewable energy (VRE) resources into their transmission and distribution systems.

Figure 1. Abstract of Laos map.

BACKGROUND: USAID SPP is the regional successor program to USAID's earlier Clean Power Asia (CPA) program, under which HNEI Grid*START* provided both collaborative (APRESA-funded) and CPA-funded support over the prior four years. Its primary goals included: 1) expanding energy capacity through the deployment of advanced energy systems, 2) increasing clean energy investments in the regional energy sector, and 3) enhancing regional energy trade. This was to ensure secure, market-driven energy sectors that support sustained economic growth. The program leveraged bilateral and multilateral partnerships, supported regional initiatives, accelerated cross-border interconnection and power trade, and established training centers for energy practitioners to develop solutions that enable Southeast Asian countries to become self-reliant and achieve their sustainable development aspirations.

Following on the accomplishments of USAID CPA, USAID SPP plans to implement numerous new activities, such as establishing a Center for Competitive Procurement (CCP), conducting a resiliency assessment of ASEAN power utilities, and undertaking capacity development efforts to support them. Toward that end, Deloitte and HNEI Grid*START* anticipate collaboration opportunities to leverage the comparative advantages of the USAID SPP and HNEI teams across all of SPP's task areas, including utility modernization, DSM/DR, energy innovation and emerging trends, competitive procurement, power trade, and grid integration.

PROJECT STATUS/RESULTS: In 2023, HNEI Grid*START* delivered updated Feasibility Study Guidelines for wind, solar, and biomass energy projects in Laos. The team also provided an updated Grid Code for Laos that incorporates interconnection standards for inverter-based resources as well as updated interconnection standards for PV systems connected at the distribution level. Additionally, HNEI conducted two capacity building sessions in June and October 2023 for EDL and MEM staff, focusing on the updated Grid Code and distribution interconnection standards.

Figure 2. Capacity building session in Vientiane, Laos in June 2023.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

I8: Energy Systems Regulatory and Technical Support for Pacific Island Countries

OBJECTIVE AND SIGNIFICANCE: Through funding under the APRESA grant from the U.S. Office of Naval Research, HNEI Grid*START* is providing technical and regulatory/policy support to various Pacific Island Countries (PIC), including the Republic of Palau (“Palau”), Cook Islands, Commonwealth of the Northern Mariana Islands (CNMI), and Republic of the Marshall Islands (RMI).

BACKGROUND: HNEI’s support for the various PICs are as follows:

- *Palau*: HNEI Grid*START* is supporting Palau’s Energy and Water Administration (PEWA) in developing key energy regulatory framework elements, modeling the national electric grid to facilitate increasing penetration of variable renewable energy, and developing technical grid interconnection requirements for new renewable generation.
- *Cook Islands*: The Cook Islands Economic Development Strategy includes a national renewable energy target of 60% by 2030, with a national commitment to a 100% renewable energy future. In support of these goals, HNEI is assisting the Cook Islands’ power company, Te Aponga Uira (TAU), with capacity building on a range of energy transition topics.
- *CNMI*: Although efforts have been made to integrate renewable energy into its power grid, CNMI still heavily depends on imported fossil fuels for its energy generation. HNEI Grid*START* is providing technical support to CNMI through a collaboration with Commonwealth Utilities Corporation (CUC), a government-owned utility company.
- RMI: As a country highly vulnerable to climate change due to its heavy dependence on imported fossil fuels for energy generation, RMI is developing an energy law and supporting regulations that must be promulgated to implement RMI’s 2018 energy roadmap.

PROJECT STATUS/RESULTS: In September 2023, HNEI Grid*START* hosted two trainings for PIC representatives in Hawaiʻi: 1) a three-day training program for the newly appointed Director of PEWA and Palau electric utility staff on a variety of energy transition policies and regulations and 2) a one-day training program for members of TAU, including Board members, the Chief Executive Officer, and the Chief Engineer. Topics covered during the training sessions included: 1) Hawaiʻi’s energy transition, 2) grid modernization, 3) battery energy storage systems, and 4) a case study on the distributed PV integration on Molokaʻi. Discussions are ongoing with TAU to further define HNEI support across a wide range of energy and regulatory needs.

At the Pacific Power Association’s (PPA) 30th Annual Conference in Saipan, HNEI Grid*START* met with a CUC Board member who expressed interest in HNEI support for their renewable integration plans. Follow-up meetings with CUC will be scheduled to identify and prioritize areas of support.

HNEI also met with representatives from RMI’s National Energy Office (NEO) during the conference, which requested a review of and comments on RMI’s new energy legislation and regulations. Further discussions with NEO will be held to finalize the scope of support.

Based in part on interactions with other stakeholders at the PPA conference, HNEI Grid*START* is also engaged in discussions with regional stakeholders to support additional energy transition and renewable energy project needs in Samoa, Tonga, the Federated States of Micronesia, Nauru, Kiribati, Tuvalu, and Niue.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023

I9: Energy Security and Resilience in the Caribbean Islands

OBJECTIVE AND SIGNIFICANCE: In February 2023, HNEI was contracted by Deloitte & Touche LLP ("Deloitte") to deliver technical assistance for the U.S.-Caribbean Partnership to Address Climate Change 2030 (PACC 2030), a U.S. Department of State (DOS) funded initiative. PACC 2030 establishes a framework aimed at enhancing U.S. cooperation with Caribbean countries to bolster climate adaptation, energy security, and resilience of critical infrastructure and local economies in the face of the climate crisis. Deloitte's role within PACC 2030 is to enhance energy security and resilience in the Caribbean through essential technical support in three key areas:

1. Supporting geothermal development in the Dominican Republic;
2. Building regulatory capacity in the realms of clean energy and utility oversight; and
3. Strengthening the technical capabilities of electric utilities and energy ministries in the integration of renewable energy, electric mobility (e-mobility), and power system resilience.

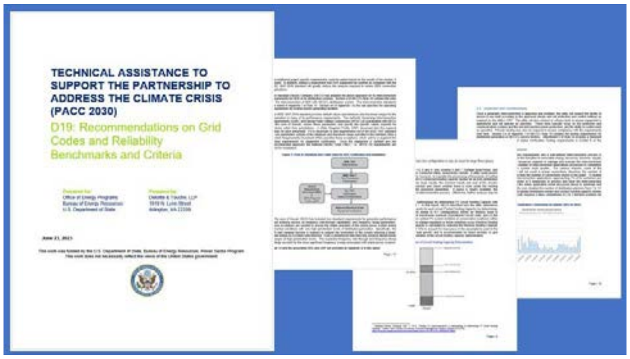
To achieve these objectives, HNEI Grid*START* is providing vital technical support on behalf of Deloitte.

BACKGROUND: The Caribbean faces the highest dependency on imported oil for power generation and the highest average electricity prices in the Western Hemisphere. This situation results in expensive and unreliable electricity, making the region vulnerable to global supply shocks. Following years of energy engagement under the Caribbean Energy Security Initiative (CESI), the Biden-Harris Administration announced PACC 2030 in June 2022 during the U.S.-hosted Summit of the Americas. PACC 2030 serves as the comprehensive framework through which all U.S. government climate and clean energy efforts will be implemented in the region.

PROJECT STATUS/RESULTS: HNEI Grid*START* is providing analytical and advisory services for various activities and deliverables outlined in its contract with Deloitte. These include:

- Conducting regional regulatory virtual training sessions for the Caribbean Electric Utility Services Corporation (CARILEC) and the Organization of Caribbean Utility Regulators (OOCUR);
- Facilitating regional regulatory in-person training sessions for CARILEC and OOCUR;
- Providing support for virtual training on ETAP Software for Barbados; and
- Preparing technical reports on a variety of topics for the following entities:
  - Jamaica Office of Utilities Regulation;
  - St. Kitts Electricity Company;
  - Trinidad and Tobago; and
  - Jamaica Public Service.

The final report entitled "*Recommendations on Grid Codes and Reliability Benchmarks and Criteria*" was submitted to the St. Kitts Electricity Company on August 4, 2023. A preliminary draft of a report entitled "*Climate Adaptation and Resilience in Trinidad and Tobago*" was also submitted to Deloitte on October 9, 2023.



TECHNICAL ASSISTANCE TO SUPPORT THE PARTNERSHIP TO ADDRESS THE CLIMATE CRISIS (PACC 2030)

D19: Recommendations on Grid Codes and Reliability Benchmarks and Criteria

Figure 1. Report submitted to the St. Kitts Electricity Company.

Additional reports for Trinidad and Tobago and Jamaica Power Service are in progress. Virtual and in-person training sessions are currently being planned and are scheduled for the first and second quarters of 2024.

Funding Source: U.S. Department of State

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2023