UNIVERSITY OF HAWAIʻI SYSTEM ANNUAL REPORT

REPORT TO THE 2023 LEGISLATURE

Annual Report from the
Hawaiʻi Natural Energy Institute

HRS 304A-1891

December 2022

Hawaiʻi Natural Energy Institute

School of Ocean and Earth Science and Technology

University of Hawaiʻi at Mānoa

Annual Report to the 2023 Legislature

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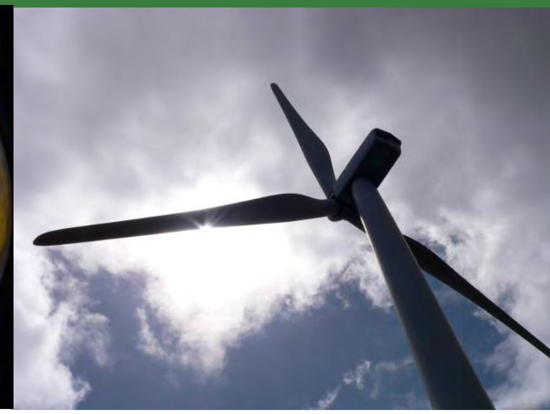


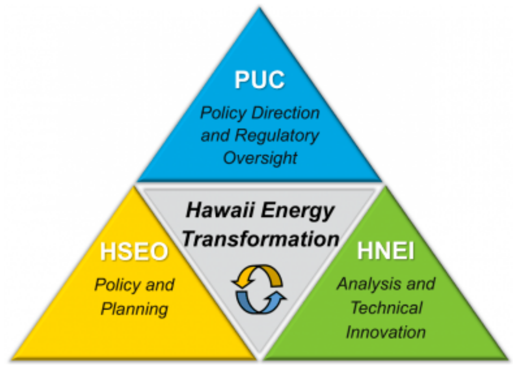
Annual Report on Activities, Expenditures, Contracts Developed, Advances in Technologies, Work in Coordination with State Agencies and Programs, and Recommendations for Proposed Legislation, required in accordance with HRS 304A-1891 (Act 253, SLH 2007).

1. INTRODUCTION

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

In 2007, the Hawaiʻi Legislature (Act 253) established HNEI in state law with an expanded mandate to coordinate with state and federal agencies to demonstrate and deploy renewable energy, energy efficiency, and peak demand reduction technologies. Act 253 (2007) also established the Energy Systems Development Special Fund (ESDSF) and directed that it be managed by HNEI. Three years later, in 2010, Act 73 authorized 10 cents of the $1.05 tax imposed on each barrel of petroleum product imported into Hawaiʻi be deposited into the ESDSF. These funds are intended to match funds from federal and private sources, and to award contracts or grants for developing and deploying renewable energy technologies. (HRS Secs. 304A-1891-1894 and Sec. 304A-2169.1).

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



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

HNEI Functions and Capabilities

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

2. STAFFING/FUNDING OVERVIEW

As an Organized Research Unit in the School of Ocean and Earth Science and Technology at the University of Hawai‘i at Mānoa (UH), HNEI receives state funding via Hawai‘i General Fund through the university budget that is sufficient to support its Director (Richard Rocheleau), three administrative support staff and partial salaries (60% to 80%) of its tenure or tenure-track faculty (permanent faculty). In 2021, HNEI's permanent faculty comprised 6 members. Permission to advertise for a seventh has been approved. The UH budget to HNEI also includes a small amount of tuition return.

HNEI has, over the past decade, consistently captured significant extramural funding, approximately $10 million per year. HNEI's primary extramural support comes from the Office of Naval Research (ONR), Naval Facilities Engineering Command, and the U.S. Department of Energy, with smaller awards from industry and other government agencies such as the U.S. Department of Interior, the Army Research Office, and the Federal Aviation Agency. HNEI's extramural awards also generate indirect funds "Research and Training Revolving Funds" of which approximately 25% is returned to HNEI to facilitate operations and research. In addition to addressing national and international needs, many of the projects funded by the entities identified above directly or indirectly support Hawai‘i's clean energy goals.

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

As part of its responsibilities under ACT 253, HNEI also administers the Energy Systems Development Special Fund (ESDSF), allocated from the environmental response, energy, and food security tax ("Barrel Tax") pursuant to HRS Section 243-3.5. The ESDSF is used to leverage funding from federal and private sources; to develop and deploy technologies to reduce Hawai‘i's dependence on fossil fuels; and to conduct analysis (often in support of the Hawai‘i Public Utilities Commission (PUC)) that directly supports Hawai‘i's transition to a clean energy economy. As documented in Appendices A through I, efforts under ESDSF include in-house work, often as cost-share that leverages other federal dollars and contracts with other organizations and consultants with specialized skills where in-house experience or availability is limited.

Generally, HNEI does not initiate legislation but, as evidenced by the project summaries in Appendix A and Appendix B, HNEI projects do inform legislators and other Hawai‘i government organizations with unbiased information and analysis on matters relevant to pending issues, bills, and proposals where appropriate. For example, HNEI provides a range of support to the PUC including detailed analytic studies for evaluation of utility proposals. HNEI is a longtime member and supporter of the Hawai‘i Energy Policy Forum (HEPF), a collaborative energy planning and policy group comprising approximately 40 representatives from business, academia, government, and non-profit organization. In 2021, HNEI assumed responsibility for coordination of the HEPF activities.

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

STAFFING	Director:	Richard E. Rocheleau
	Permanent Faculty (FTE)	6
	Other permanent staff (APT)	3
	Temporary Faculty	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.

EXPENDITURES:	General Funds	$1,364,916
	Tuition and Fees S Funds	$49,897
	Research and Training Revolving	$351,258
	Extramural Awards	$9,505,497
	Energy Systems Development Special Fund	$868,019

3. RESEARCH SUMMARIES

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

In 2022, within these areas, HNEI conducted or provided leadership for 54 discrete projects. The various activities and key accomplishments under each of these projects are summarized in a series of summaries included within the nine Appendices of this report. These "Research Highlights" provide a concise description of active HNEI research projects in an easily accessible format. Many contain links to more detailed reports, papers, and descriptions of HNEI's work activities that are also available on its website (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 Appendices follows.

Appendix A: Hawai‘i Energy Analysis and Policy

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

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

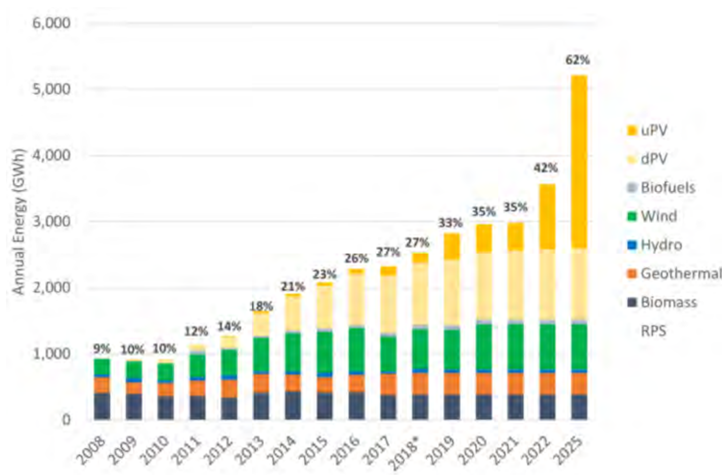


Figure 1

Figure 1 shows the expected production of electricity by resource for the three HECO company systems assuming full buildout of the Stage 2 systems. In its report to the 2021 legislature, HNEI emphasized its efforts, in partnership with Telos Energy, to apply previously developed analytic tools to a variety of reliability issues facing the island grids with significant attention to the pending retirement of the AES coal plant. In 2022, these tools were further developed to address the continuing delays in the planned PV + storage projects and unexpected unit outages on both O‘ahu and Maui. Appendices A4 through A6: O‘ahu Grid Reliability, Clean Firm Energy Needs, and Maui Reliability and Kahului Retirement Analysis summarize these efforts. The results of this work has been presented and is being used by HECO and the PUC in their decision making.

In 2022, HNEI also initiated two additional analytic efforts: DER Aggregation and Control with High Penetration Solar + Storage (Appendix A7) to examine the level of control required to optimize grid benefits from distributed solar resources and Hawai‘i Hydrogen Integration Study

(Appendix A8) to begin examining the potential role of hydrogen for grid services and other applications.

In addition to the technical analyses, HNEI continues to work with the State Energy Office and the Hawaiʻi Public Utilities Commission to support state energy policy and Hawaiʻi's energy transformation (Appendices A1 through A3). These activities include Decision Support Services to the Hawaiʻi PUC, support of the HECO's Integrated Grid Planning efforts, and management of the Hawaiʻi Energy Policy Forum based on the UH Mānoa Campus. Appendix A9 is a short summary of HNEI's work to assist the Department of Health to develop policies for the future disposal of electronic waste including PV and batteries. The final report for this effort was submitted separately to the Legislature and is also available on HNEI's website. Appendix A10 provides an update of the U.S. Department of Energy funded Energy Transitions Island Partnership Program intended to provide analysis, technical assistance, and policy guidance to address high energy costs, reliability, and inadequate infrastructure challenges faced by island and remote communities.

Appendix B: 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 barrel tax.

Appendices B1 through B6 summarize six 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, completion of an energy resilience study for Marine Corps Base Hawaiʻi, continued development and demonstration of a virtual power plant on Maui, development and deployment of a bidirectional EV charging system on the UH campus for optimized ride sharing, and an AI-based microgrid platform at Natural Energy Laboratory of Hawaiʻi Authority (NELHA).

Appendix C: Alternative Fuels

Alternative fuels have always been an important component of Hawai‘i's efforts to reduce its dependence on imported petroleum and an essential component for reducing Hawai‘i's greenhouse gas footprint. While early projects focused primarily on power and ground transportation applications, sustainable aviation fuels are garnering increased interest in Hawai‘i and nationally. Within this topical area, HNEI conducts research, testing, and evaluation that seeks to support the potential for alternative fuels production in Hawai‘i. Projects include two projects (Appendices C1 and C2) focused on sustainable aviation fuels and one focused on enhanced fuels characterization methodologies (Appendix C3). HNEI is also actively researching the production of novel biocarbon materials using a slow pyrolysis process (Appendix C4) and novel processes for production of solar fuels, with primary emphasis on photoelectrochemical hydrogen production (Appendix C5).

Appendix D: Electrochemical Power Systems

For almost two decades, HNEI has been conducting research, development, and testing of fuel cell and battery technologies. The primary goal of these efforts has been to understand the performance and durability of these electrochemical technologies for both commercial and military applications, including fuel cell powered and electric vehicles, fuel cell powered unmanned (autonomous) aerial and undersea vehicles, and for grid services. Appendix D1 summarizes HNEI's ongoing partnership with the Naval Research Laboratory to develop reliable fuel cell power systems for unmanned aerial vehicles. Appendices D2 through D8 describe multiple approaches for development of more efficient, lower-cost fuel cells, including both proton-exchange and anion-exchange membrane technologies. Appendices D9 through D12 describe various efforts intended to inform the use of Li-ion energy storage systems. Finally, Appendix D13 describes a nascent program to develop new, lower cost battery technologies. More detailed descriptions of each of these efforts are found in Appendix D.

Appendix E: Advanced Materials

The five projects included in the Advanced Materials group, include development of novel techniques for the production of low cost photovoltaics (Appendix E1); two projects focused on the development of low cost, high performance hydrogen storage technologies (Appendices E2 and E3); an ongoing effort to develop novel solutions for forward osmosis seawater desalination (Appendix E4); and a description of a research and education collaboration with the University of Washington, funded by the National Science Foundation, to develop foundational knowledge about advanced defect-bearing and doped materials and the properties and their potential use for future energy technologies.

Appendix F: Energy Efficiency and Transportation

The three projects included in the HNEI energy efficiency and transportation portfolio have potential near-term value to Hawai‘i. Appendix F1 describes a combined field measurement and modeling effort intended to better understand the role of ventilation in various building typographies, using Hawai‘i Public School classrooms as the model. Appendix F2 summarizes a project providing technical support and content development to the City and County of Honolulu Climate Change Commission (CCC), for development of a Commission white paper intended to provided technical and policy guidance to the building industry and city leaders in the context of climate change mitigation. Appendix F3 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 Hawai‘i Island Mass Transit Agency (Hele-on bus).

Appendix G: 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 H: International Support

In 2017, HNEI was the recipient of a multimillion-dollar award from the Office of Naval Research titled "Asia-Pacific Regional Energy Systems Assessment (APRESA)," intended to facilitate development of clean, resilient, efficient energy systems throughout the Asia-Pacific region. 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 H1 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 H2 through H5 provide additional detail of selects projects from Appendix H1. Appendices H6 through H10 summarizes the recent work supported by USAID and the World Bank (via subcontracts to the prime).

APPENDICES

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 includes 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.

A number of issues related to the integration of renewable energy technologies are discussed in more detail in other project summaries located in Appendix A. Other examples of past support included a review of HECO's distributed energy resources (DER) Grid Service definitions and the economic merits of HECO's standalone battery proposals.

PROJECT STATUS/RESULTS: This paper briefly discusses four recent examples of HNEI support to the PUC:

- AES retirement and replacement;
- Maui oil unit retirement and replacement;
- Firm renewable needs; and
- Lifecycle analysis of greenhouse gases for Hawaiʻi relevant generating technologies

AES Retirement and Replacement: 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. 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), Oʻahu is currently in a supply deficit until other Stage 1 and 2 solar + storage resources become available.

Maui Reliability and Kahului Retirement Analysis: 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 on replacement resources. In addition, the Maalaea M10-M13 diesel engine may need to be retired earlier than expected. The objective of this study was to update the 2021 analysis and reevaluate Maui 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 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. This work is described in more detail in Appendix A6.

Clean Firm Needs: 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. This work is described in more detail in Appendix A5. A more complete report will be completed prior to the 2023 legislative session.

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

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

While some renewable energy generation technologies do not emit CO_2 at the point of use, there usually are embedded emissions that are created during the full life cycle of the technology. A full accounting of emissions requires that emissions that arise from these other steps, such as production (mining and manufacturing), operation and maintenance, and disposal/reuse, be included. In other words, the life-cycle of all energy technology will have some GHG emissions, even if the actual production of electricity does not produce any GHGs. Based on the literature and additional analysis conducted by HNEI, the range of estimates for lifecycle emissions was found to be wider than expected. Even for well-defined technologies, such as PV, substantial ranges were found, partly due to variations in the technology but largely due to variations the manufacture of the components.

For other technologies, such as biomass and biofuels, existing studies can provide general guidance, but variation in the type of feedstock, the conversion technology, and the final disposition of waste – for example, the re-growth of new biomass resources – requires comprehensive site-specific studies. For biomass and biodiesel combustion, large amounts of CO_2 may be emitted at time of generation, but depending upon the biomass source, operations, and life-cycle assumptions, considerable offset of these emissions is possible through new plantings or sequestration. Recently, some publications offer contradictory conclusions regarding biomass emissions and their timing. These conclusions are based on the temporal differences in terms of the immediate combustion of biomass-derived fuels and the time it takes to regenerate these resources. HNEI is evaluating these analyses and will incorporate the findings in this deliverable to the PUC.

Following the development of the draft deliverable, HNEI will convene a meeting of stakeholders from Hawai'i and experts from the U.S. Department of Energy's (DOE) national laboratory system. HNEI expects to convene this expert panel in early 2023 with a final report to the PUC by June 2023.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2022

A2: Support of Integrated Grid Planning

OBJECTIVE AND SIGNIFICANCE: In 2018, under guidance from the Hawai‘i 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.

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

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 insight to using "bookends" to delineate the potential impacts of load uncertainty. During 2021, significant effort was expended by HNEI to quantify alternative methodologies and metrics from using energy reserve margins (ERM) in determining resource adequacy. These probabilistic tools were used in the analysis of grid reliability with the pending AES coal plant retirement.

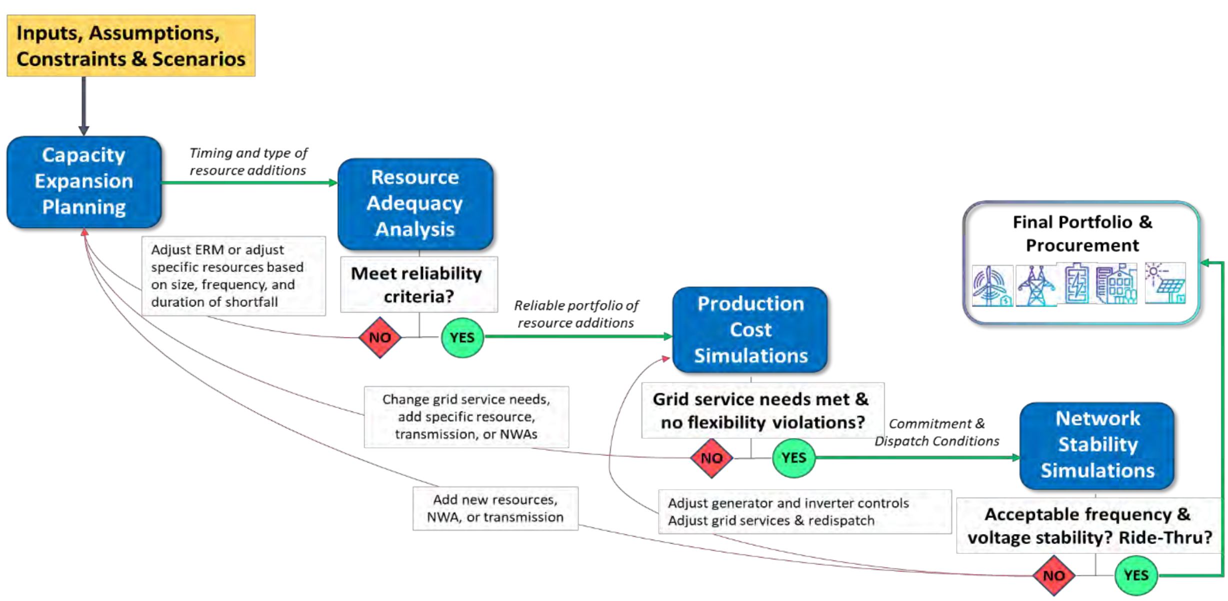


Figure 1. HNEI Modeling Framework Adopted by the IGP.

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

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 in other parts of the IGP stakeholder process, including active involvement in the Stakeholder Committee, the Stakeholder Technical Working Group, and other relevant Technical Working Groups, such as the newly formulated Distribution sub-committee, the Transmission sub-committee, and the Resource Adequacy sub-committee.

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

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

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2022

A3: 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 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 sponsors and organizes a Legislative Briefing at the Capitol at the opening of each legislative session, an annual Hawaiʻi Clean Energy Day event, and sponsors programs to develop reliable information and educate and raise awareness in the community. 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: 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 Nov. 15, 2021 could be used to address the most vulnerable aspects of that infrastructure.

In response to the critical needs addressed, 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.
- 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 is also a key contributor to ETIPP, the U.S. Department of Energy's Energy Transitions Initiative Partnership Project, working alongside remote, island, and island communities seeking to transform their energy systems and increase energy resilience through strategic energy planning and the implementation of solutions that address their specific challenges.

Funding Source: Energy Systems Development Special Fund

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Last Updated: November 2022

A4: Oʻahu Grid Reliability

OBJECTIVE AND SIGNIFICANCE: 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 conducted extensive reliability analysis of the retirement to brief HECO, the Hawaiʻi 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 Oʻahu, and in particular, informing stakeholders on the implications of future fossil fuel plant retirements.

KEY RESULTS: Stochastic analysis, using the tools developed by the HNEI-Telos Energy team and reported last year, are being used to assess capacity reliability risks associated with the AES retirement, updates for utility plans, and possible impacts due to delays in project schedules, 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), Oʻahu is currently in a supply deficit until other Stage 1 and 2 solar + storage resources become available.

However, recent trends in the Oʻahu peak load which are still approximately 100 MW lower than pre-pandemic levels, mitigate much of the reliability risk through the end of 2022 and early 2023.

With the 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 Hawaiʻi 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.

In 2020, SB 2629 was enacted which bans coal-fired generation in Hawaiʻi after 2022, ensuring the AES retirement. The objective of this ongoing study, requested by the PUC, is to evaluate the ability of the planned Stage 1 and Stage 2 utility scale solar + storage plants to provide the capacity resources needed to ensure reliable grid operations 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. At the end of 2022, only one of the projects is online and operating, with the remaining projects not expected before April 2023. 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 Oʻahu that required a re-evaluation of Oʻahu's grid reliability:

1. Continued project delays across most of the Stage 1 and Stage 2 projects. The primary AES capacity replacement (185 MW standalone KES BESS) is now delayed until May 2023, and other solar + storage projects are delayed until Q3 or Q4 of 2023;
2. The Kahe 4 (90 MW) oil generator was removed from service due to equipment failure in July 2022. This plant is not expected back online until late Spring 2023 at the earliest while repairs take place;
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; and

4. Oʻahu 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 Appendix A1 in HNEI's Report to the 2021 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.

PROJECT STATUS/RESULTS: The stochastic methodology is being used to evaluate the reliability the Oʻahu 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: 39 MW (Mililani), 89 MW (+Waiawa & West Oʻahu), and 139 MW (+Hoʻohana); three peak load levels: 1085 (2022 data), 1150 (IGP), and 1215 MW (2017-2019 data); and three forced outage rates: 7.5 (2015-2019), 11 (midrange), and 15% (2020, 2021). Each of these cases was evaluated with and without the Kapolei battery for a total of 54 scenarios.

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

Outage Draws

Solar Years

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

Base Case

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

AES Retired + Stage 1

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

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.

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 (as of November 2022), and load returning to pre-pandemic levels by Fall of 2023.

These results indicated that resource adequacy risk will remain elevated relative to historical norms (Reference Point) until replacement resources start coming online in April 2022. By Fall 2023, reliability is at or below historical norms, even with a large return of load, in all cases but the high forced outage rates.

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

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Last Updated: November 2022

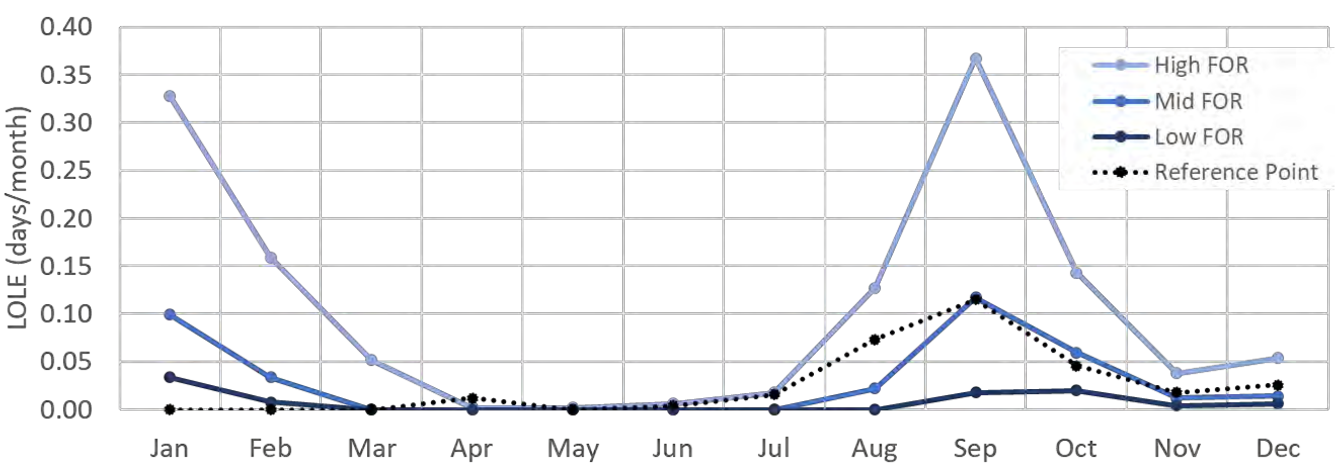

Figure 3. Expected monthly loss of load expectation based on current proposed schedules and returning load.

A5: Clean Firm Needs

OBJECTIVE AND SIGNIFICANCE: This study was intended to inform ongoing procurement and proposed legislation for both variable and firm renewable energy. It seeks to determine the minimum amount of firm power that the system would require at various levels of wind, solar, and storage additions. This will also inform 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.

KEY RESULTS: The results of this study help frame the ongoing discussions, debates, and planning related to the role of firm renewable energy. The findings indicate that on Oʻahu, even with very high penetration of energy from variable renewable energy and storage grid (e.g. over 70% by energy), there is a need for firm capacity of 600-750 MW. While the need for capacity remains, the use of these systems decreases significantly as the penetration of the variable generation increases. In this future clean energy system, these resources would run sparingly. However, when they do run, it could be for multiple consecutive days at a time. This detailed analysis of firm energy need will help identify potential resources to provide this unique grid service and help inform recommendations for policymakers, regulators, and grid planners related to the long-term role of firm renewables.

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.

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 and imposed limits on any one type of renewable energy source. While these laws are not in statute today, there is continued interest in firm renewable energy and likely the topic of future legislative sessions.

In addition, on March 1, 2022, Hawaiian Electric 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."

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 the island of Oʻahu, and later expanded to evaluate needs statewide.

In order to quantify potential firm renewable needs, the study team developed a simplified screening methodology that was verified with robust probabilistic resource adequacy and detailed

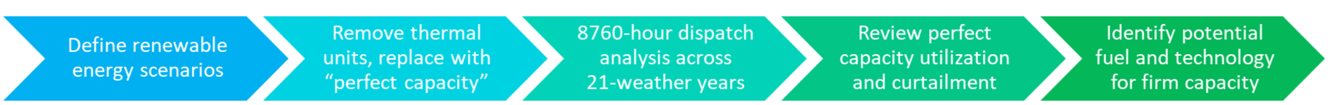

Figure 1. Five-step screening methodology to calculate firm renewable needs.

operational modeling of a specific resource mix. The screening methodology was conducted in a five-step process (Figure 1 on the previous page).

The study team developed a limited number of potential future variable-renewable resource mixes able to provide up to 90% of the island's energy needs. This was done by varying the amount of solar + storage and offshore wind resources in 1,000 GWh per year intervals. These scenarios were then evaluated without the existing oil capacity on the system to estimate the remaining amount of capacity and energy needed after maximizing the use of the solar, wind, and battery energy storage. These firm energy additions were assumed to be always available and perfectly flexible allowing them to operate in a manner which would minimize the 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 (Figure 2).

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

The results of the simulations were then evaluated to quantify system performance and firm renewable capacity needs. In particular, the metrics evaluated 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 mix or a future firm renewable resource mix.

Results of the analysis are provided in Figure 3 on the following page which compares two resource portfolios at various levels of variable renewable energy. Only the maximum dispatch of the perfect capacity resource is shown, illustrating the aggregate *capacity* need of 500-750 MW, 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.

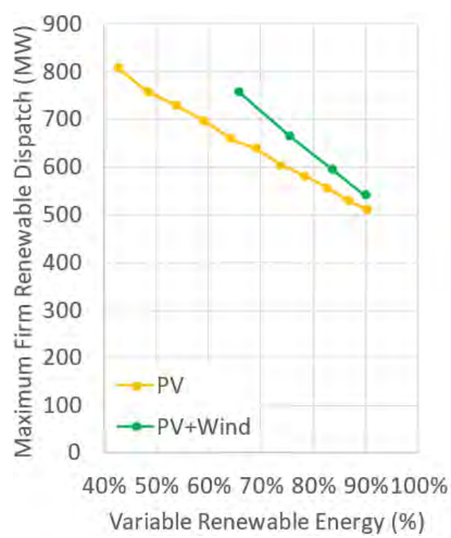

Figure 3. Firm capacity needs at increasing levels of variable renewable energy.

However, the analysis also investigated 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 of between 500 and 700 MW. 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 also repeated at various levels of electric vehicle integration. The results indicate that a 20% increase in EV charging during peak demand periods would only increase the firm renewable requirement by approximately 50 MW, which would increase to an approximately 250 MW increase in the 60% EV peak charging scenario. In addition, the differences between the charging profiles were relatively modest. 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, but the timing of EV charging has a relatively modest impact on overall firm renewable needs for reliability.

The analysis concluded with an evaluation of specific firm renewable technologies that may play a role in meeting the system's firm capacity needs. This included a review of biomass and biodiesel, geothermal, OTEC, hydrogen, and long duration storage resources. Each resource was discussed based on technical potential, feasibility, and land use considerations.

This study is intended to be a preliminary analysis of the potential firm renewable needs for the future Oʻahu system and to help inform proposed legislation and utility procurements. In the light of the Hawaiʻi 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. A more complete reporting of these results is expected prior to the start of the 2023 legislative session. 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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A6: Maui Reliability and Kahului Retirement Analysis

OBJECTIVE AND SIGNIFICANCE: The Kahului Power Plant (KPP) is scheduled to retire by the end of 2024. Analysis conducted in 2021 showed how the retirement could be reliably achieved with proposed solar + storage projects. Since that analysis was completed, project delays have occurred on the installation of the replacement resources. In addition, the Maalaea M10-M13 diesel generators may need to be retired earlier than expected due to a shortage of parts. The objective of this study was to update the 2021 analysis and re-evaluate 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 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). The analysis showed that, with only one thermal plant retirement, even partial deployment of proposed hybrid solar + storage projects would improve system reliability compared to current reliability levels. However, full deployment of all proposed resources was 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 lower than that experienced during the Oʻahu AES coal plant replacement.

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

> *"The KPP Transition Plan has several key components: (1) the Stage 1 and Stage 2 RFP projects will provide capacity and energy replacement and grid services; (2) the K3 and K4 generating units of KPP will be converted and repurposed to synchronous condensers to replace critical voltage support service and synchronous inertial response provided by KPP, among other essential grid services; (3) the Waena Switchyard project will maintain functionality and reliability of the transmission system serving Maui in the absence of KPP, avoid circuit overloads, and reliably integrate new renewable resources; and (4) contingency plans that include DER grid service programs and a review of generator maintenance schedules as needed."*[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, pushing these dates back to 2023-Q4 2024. Some projects may also be withdrawn due to community opposition, supply chain disruptions, and increased project costs.

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 a response to your each RFQ."[2]

[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.

PROJECT STATUS/RESULTS: 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 and recently adopted by HECO. It utilizes sequential Monte Carlo probabilistic modeling which incorporated 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 Oʻahu.

Grid simulations were conducted across seven scenarios with assumptions on load, DER integration, and other system details derived from HECO's Integrated Grid Planning assumptions for the year 2024. The Reference Point scenario assumed the current grid's resource mix, including KPP 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 83 MW.

Each of these scenarios was evaluated without any replacement resources, and across a range of Stage 1 and 2 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.

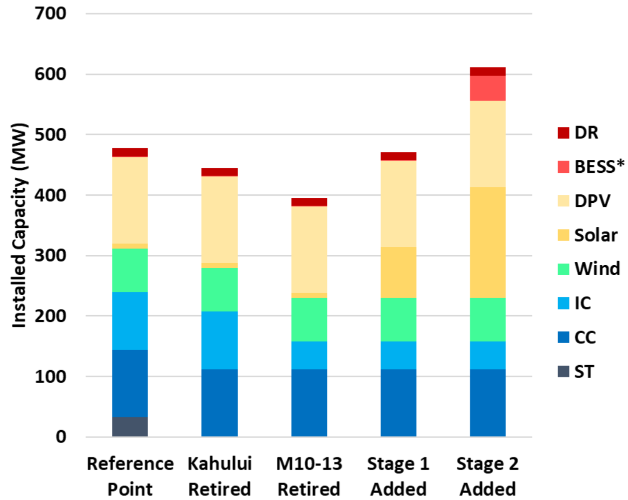

Figure 1. Installed Capacity by Scenario.

Each scenario was analyzed across 440 random samples (replications) of chronological dispatch – representing 22 years of weather data (22 solar, 8 wind) and 20 outage profiles per weather year (440 total). The output of the analysis included the number, the magnitude, and the duration of the capacity shortfall events that occur when there are not enough available resources to serve load.

Results of the analysis are provided in Figure 2 on the following page 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 60 and 80 MW, illustrating the diminishing returns of solar + storage resources to replace oil capacity. With both oil plants retired (-83.5), up to 160-175 MW of replacement solar + storage capacity would be required to maintain reliability. This highlights the fact that full deployment of the Stage 1 and Stage 2 hybrid solar + storage resources would be required to meet current system reliability levels. However, system reliability could be improved further with the addition of the Waena BESS.

These results were shared with the PUC, HECO, and the ACET to support ongoing planning in the state and continued monitoring of Stage 1 & 2 replacement schedules.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2022

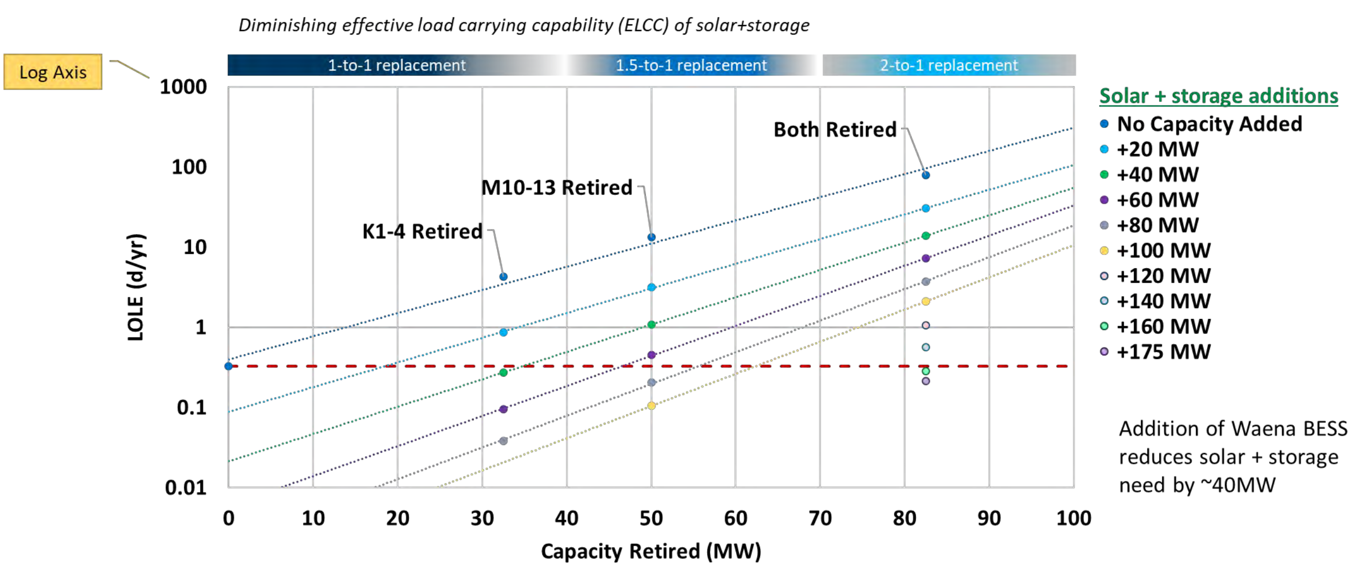

Figure 2. Loss of Load Expectation with oil retirements and solar + storage replacement.

A7: DER Aggregation and Control with High Penetration Solar + Storage

OBJECTIVE AND SIGNIFICANCE: Over the past decade, the Oʻahu power grid has integrated significant amounts of solar PV, with over 550 MW of uncontrollable and unobservable distributed (rooftop) PV and 190 MW of utility-scale PV currently installed. As a result of the limited room available on the grid for uncontrolled assets, there is significant focus on controllability of all assets, including the distributed systems. However, recent developments that include large amounts of battery storage and new options for grid flexibility, have created new opportunities to integrate distributed rooftop PV at the system level without real-time control. The objective of this study is to quantify the level of control needed for additional DER based on system (not circuit) hosting capacity constraints.

KEY RESULTS: Preliminary results of this recently initiated analysis indicate that there is no appreciable difference in system curtailment or operating costs between DER (distributed PV + batteries) deployed with full real-time utility control and a simple time-of-day control system without direct management. The implications for this finding are far-reaching and have potentially large impacts on the design of future DER programs across the state. Specifically, simple passive and autonomous controls at the customer level appears to provide sufficient grid support to allow additional distributed PV deployment, without the need for costly communications, control systems, and payments for DER grid services.

Because of the implications of this preliminary analysis in directing future DER policy, particularly on Oʻahu's power system, future work is planned to address questions such as:

- Do existing programs effectively incentivize the "No Utility Control" systems?
- Do transportation electrification, TOU rates, or demand-side management change the fundamental finding?
- Do these preliminary results hold for higher amounts of system-wide PV, approaching the 100% RPS?
- How might distribution circuit-level constraints impact the analysis? What about operational reserve requirements?
- How would this result be impacted by lower levels of utility scale storage than Oʻahu's planned system?

It's important to note that this analysis did not evaluate coordination and control of DER that might be required for circuit-level hosting capacity constraints at specific locations. This is another topic for future work.

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

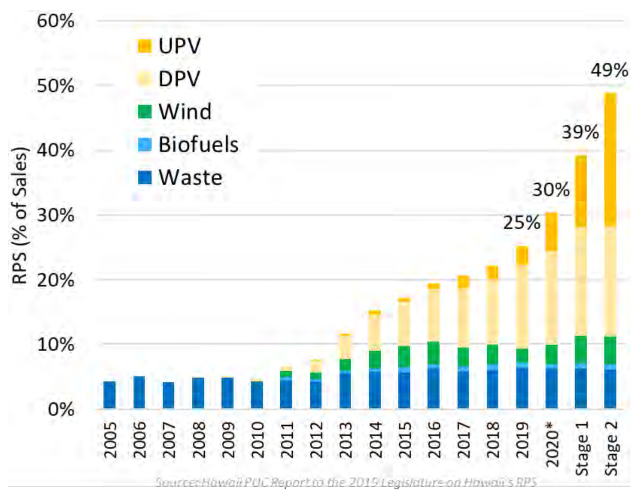

Figure 1. Oʻahu RPS Growth 2005-2020, and Stage 1 + 2.

These changes are taking place against the backdrop of other significant changes to the grid that could enable further economy-wide decarbonization. Most notably are the retirement of the AES coal plant, the largest fossil fuel-based generator on the Oʻahu grid, and the addition of the standalone Kapolei battery that can charge during the day using surplus solar resources. These storage systems, both the PV connected and the stand-alone Kapolei BESS, can also provide grid services that were traditionally provided by the steam oil fleet. As a result, the grid will soon be significantly more flexible than a traditional system. At the same time, transportation and other end uses are being electrified, leading to a more dynamic and changing demand side.

PROJECT STATUS/RESULTS: In this work, analysis was conducted to evaluate the need for aggregation and control of additional distributed solar + storage (DER) deployments. To quantify this value, a series of production cost grid simulations were conducted at increasing solar penetrations, increasing by 100 MWac blocks of installed distributed solar capacity. Each PV block was added with two different storage capacity configurations. The production cost models simulate grid operations across all 8,760 hours per year and incorporate fluctuating loads, solar, and wind resources. The remaining grid resources, including thermal generation and battery energy storage, are economically scheduled to serve load in a least-cost manner subject to utility defined operational limitations and transmission constraints. If the underlying generation mix does not have ample flexibility (either storage to charge using surplus solar or ability of thermal generators to cycle offline) solar may be curtailed and unused.

The benefits of DER aggregation and control were evaluated by simulating two bookend scenarios (Figure 2)**Error! Reference source not found.**.

Figure 2. Overview of DER control schemes.

As additional PV is added to the grid, not all of it can be accepted, even when combined with the storage configurations that were evaluated. The resulting incremental solar curtailment, assuming full control, with increasing solar deployment is provided in Figure 3. Results are shown assuming two storage configurations and at two DER Control Schemes.

The results indicate that there are no differences in curtailment between cases with full utility control and when systems follow a fixed profile. This is because there is ample flexibility on the remaining utility-scale hybrid solar + storage resources to adjust to the static DER profile. In addition, the results showed no appreciable difference in total system generation cost because there was no change in oil-fired generation and grid services were already saturated by the utility-scale storage systems.

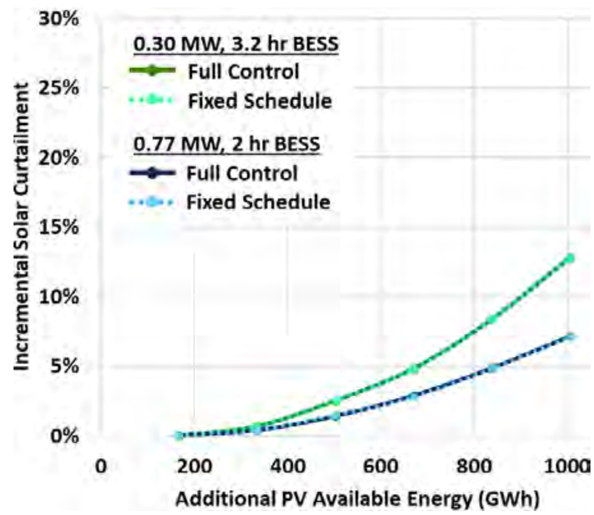

Figure 3. Curtailment of solar resources with and without utility control.

These results support two key conclusions:

1. There is no need for direct communication and control of DER resources to avoid system curtailment if behind the meter storage shifts energy out of the middle of the day via a simple rules-based approach; and
2. There is no economic benefit of DER control and coordination once there is sufficient utility-scale storage resources available on the system. The flexibility and grid service benefits saturate once a certain amount of battery storage is installed.

This finding indicates that programs to require or compensate DER resources for coordination and control may not be necessary once sufficient grid scale storage is available to the system operator. Well-designed tariffs and autonomous response of DER to grid conditions may be sufficient for further DER integration, but additional research is underway to validate this initial finding.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2022

A8: Hawaiʻi Hydrogen Integration Study

OBJECTIVE AND SIGNIFICANCE: HNEI initiated a study in 2022 that will evaluate the potential for hydrogen (H_2) production and grid integration in Hawaiʻi, with expected completion in 2023. The objective of this study is twofold. Initially, it seeks to categorize the potential use cases for H_2 in Hawaiʻi and quantify the power sector requirements for producing H_2 locally. Local H_2 production analysis can also be used for comparison against importing H_2 products. After H_2 needs are assessed, the integration of H_2 production into the electric grids across the state will be studied. The integration studies seek to determine the benefits and operational limitations of different H_2 electrolysis options and the power system requirements to satisfy Hawaiʻi's potential H_2 needs.

This study will also focus specifically on the power sector requirements for clean dispatchable resources and compare the H_2 integration for electric power use to other clean alternatives, such as long duration energy storage, geothermal, biodiesel, and other firm renewable technologies.

KEY RESULTS: While hydrogen may play an important role in long-term decarbonization, there exists uncertainty whether advancements in electrification will cut into potential hydrogen market shares. The round-trip efficiency differences between direct electrification and hydrogen use means that direct electrification is likely to be favorable if it is feasible for the end use. The following petroleum end uses in Hawaiʻi may require hydrogen substitution of some form to fully decarbonize while other sectors will likely pursue electrification options:

- ***Aviation***: Opportunities for short-haul inter-island flights to be electrified;
- ***Medium/heavy duty vehicles***: Battery technology improvements could decrease fuel cell vehicle demand or replace them fully;
- ***Construction***: Heavy machinery, steel, cement, asphalt;
- ***Agriculture***: Remote locations may make grid charging difficult to manage; and
- ***Oil refining/chemical processes***: Residual petroleum for industrial products may require hydrogen.

BACKGROUND: In Hawaiʻi, there is also continued interest in H_2 production and end use. During the most recent legislative session, multiple bills were proposed to encourage the development of an H_2 industry in Hawaiʻi. HB1611 proposed a State Energy Plan that specifically addressed firm renewable options, including H_2, across Hawaiʻi.

HB1937 required the Hawaiʻi Natural Energy Institute to develop a H_2 Strategic Plan for Hawaiʻi examining 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, identification of end-use markets, permitting requirements, hydrogen for transportation and grid, techno-economic feasibility, and environmental benefits for resiliency, in comparison to imported hydrogen. The HNEI-Telos study, outlined in this document, is a first step of this Strategic Plan.

At a national level, the recent passage of both the infrastructure and jobs act (IIJA) and inflation reduction act (IRA) has created substantial momentum in the energy industry for producing clean hydrogen. Of most importance, is the ability for hydrogen to displace fossil fuel use in hard to abate sectors where electrification cannot meet all sector needs. Hard to abate sectors (e.g., aviation fuel) represent a significant portion of Hawaiʻi's current petroleum import needs and source of greenhouse gas emissions.

In addition, many prospective entities are developing hydrogen proposals for the U.S. Department of Energy (DOE) hydrogen hub grants around the country, including in Hawaiʻi. Multiple stakeholders in Hawaiʻi are pursuing DOE funding for a local "hydrogen hub" in the state. However, identification of the amount of useful hydrogen needed to decarbonize the economy, including an assessment of integrating hydrogen production in a high variable renewable energy grid has not yet been widely pursued. This study will serve as an initial basis for future hydrogen analysis in Hawaiʻi as decarbonization goals progress.

PROJECT STATUS/RESULTS: A review of current petroleum and natural gas flows to end-use sectors is currently underway. Pre-COVID 2018 and 2019 petroleum use by end-use sector is available from the Hawaiʻi State Energy Office (HSEO) and the U.S.

Energy Information Agency (EIA). This data serves as the basis for determining the proportion of primary energy input that can either be electrified or require H_2 conversion.

Table 1. 2018 Petroleum Use by End Use Sector (from HSEO 2020 HI Energy Facts and Figures).

HSEO End-Use Sector	Total 2018 Petroleum Usage (%)
Transportation	65%
Electric Power	24%
Industrial	8%
Commercial	3%
Residential	0.3%

Of the end-use sectors referenced in Table 1, Transportation and Electric Power make up the bulk of petroleum usage, but also present significant electrification potential. Disaggregating the end-use sectors into granular energy uses, such as light versus heavy duty vehicle input is required to assess electrification potential versus H_2 potential. This is the current state of phase one for the H_2 integration study. Analysis of available HSEO, Hawaiʻi Department of Business, Economic Development & Tourism (DBEDT), and the EIA State Energy Data System (SEDS) energy use data will be used to disaggregate sectors (Figure 1).

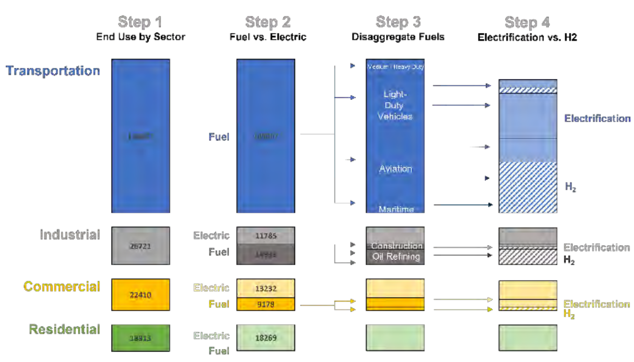

Figure 1. Example of the disaggregation of end use sector energy input into electrification versus H_2.

Building off the statewide review of potential H_2 end-uses, future electricity demand profiles will be developed. These profiles will reflect different electrification futures with different splits between electricity and molecules (hydrogen) for energy inputs. An example of this could be a future where electrification potential increases beyond electric power and light-duty vehicle needs, translating to lower H_2 demand.

For each electrification/H_2 scenario developed, the amount of H_2 production needed on a yearly and monthly basis will be used to characterize electrolyzer and electric power needs. The H_2 needs for each scenario will be modeled using production cost software to assess three hydrogen integration pathways to meet each future scenarios H_2 need.

The following hydrogen integration pathways present different grid integration and production challenges for H_2 to serve industrial and electric power needs. Electrolysis production factors kept consistent between H_2 configurations will be electrolyzer efficiencies, minimum operating durations, load flexibility, and H_2 storage configurations including the impact on round trip efficiency of the H_2 systems.

- **Baseload**, high capacity factor, low capacity (small electrolyzer size) which curtails only during extreme electric power shortages. This configuration maximizes electrolyzer utilization.
- **Self-supply**, electrolyzer load brings a separate portfolio of renewable energy resources but still operates with grid energy.
- **Grid-supply**, low capacity factor, high capacity (large electrolyzer size) targeting surplus renewable energy periods. This configuration is more price sensitive and grid buildout heavily influences hydrogen production load.

The H_2 integration study will inform the operational requirements for future H_2 load to serve multiple purposes in a decarbonized Hawaiʻi economy. The study will focus on several important integration questions; key questions are included below for context:

- How much H_2 storage is required to meet multiple H_2 end-use demands? How much is strictly for long duration energy storage?
- What impact does H_2 load have on statewide electricity curtailments?
- 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?

This study is a first step in developing Hawai‘i's hydrogen economy. It will inform economic and energy planners on the impact that integrating hydrogen production will have on Hawai‘i's grid.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2022

A9: Disposal and Recycling of Clean Energy Products in Hawaiʻi

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

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

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

PROJECT STATUS/RESULTS: This project commenced in September 2021 and remains ongoing. Findings to date includes 1) identifying material composition of PV panels, inverters, cabling, and mounting equipment as a function of installed power (kg/kW), 2) cumulative installed PV by island for residential, commercial, and utility scale since 2005, 3) the projected loading rate of aging PV materials as far out as 2045, 4) preliminary estimates of installed battery capacity as residential, commercial, and utility scale, and 5) estimates of material composition of PV battery as a function of installed power (kg/kW).

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. This suggests that the total amount of these PV related clean energy materials installed to date total 8.8% of all municipal solid waste and commercial/demolition waste generated across the entire State in 2021.

These and other results have been summarized in detail in a separate report to be submitted to the legislature in January of 2022.

Funding Source: Energy Systems Development Special Fund

Contact: Michael Cooney, mcooney@hawaii.edu

Last Updated: November 2022

A10: Energy Transition Initiative Partnership Program (ETIPP)

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 of 2020, HNEI was selected via a competitive solicitation to be the Pacific Regional Partner, one of five regional partners initially selected nationwide to: 1) solve critical questions and issues of importance by communities engaged in energy transitions and 2) support replicable energy transition technical assistance and knowledge sharing to inform and support energy transitions throughout the United States.

BACKGROUND: 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 and the scoping of the three Cohort 2 projects in the Pacific Region. The 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.

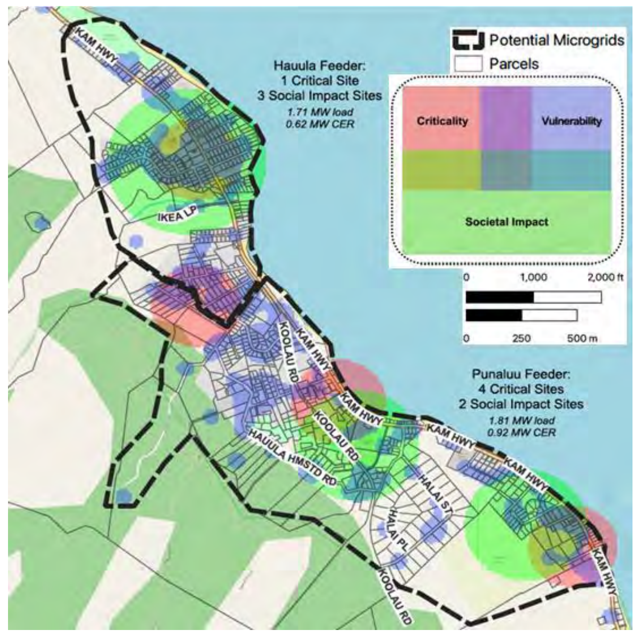

Figure 1. Potential Hauʻula sites for hybrid microgrids.

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.

The three selected Cohort 2 projects in the Pacific Region during 2022 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 will conduct an energy needs assessment and collaborate 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 will conduct analysis on building heating and cooling loads at select locations and support NREL's modeling of shallow geologic conditions and at each campus 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 from NREL and HNEI on renewable energy resource integration, improved utility planning and energy security, and to establish a performance management system for its Clean Energy Master Plan.

Funding Source: U.S. Department of Energy

Contact: Mark B. Glick, mbglick@hawaii.edu

Last Updated: November 2022

Hawaiʻi Natural Energy Institute Research Highlights

Appendix B: Grid Technology Development

B1: 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), located in Kāneʻohe Bay, Oʻahu. The project objective is to demonstrate and assess the reliability, resilience, and energy efficiency benefits of a DC microgrid serving two HIMB buildings. The system 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: Among HIMB's goals is for the island and its research facilities to serve as a model for sustainable systems. Thus, it is an ideal site for a renewable energy technology-based microgrid test bed that represents a remote location vulnerable to energy disruption, yet serving mission critical power needs. Key project goals include: 1) adoption of innovative energy efficient and reliable clean energy technologies; 2) establishment of a research platform to study resilient DC microgrid technologies (e.g., microgrid controller, energy storage, DC powered appliances, etc.) in a tropical coastal environment; and 3) development of solar DC powered all-electric land (e-car) and sea (e-boat) transportation solutions. International partnerships with the Okinawa Institute of Science and Technology (OIST), Japan, PUES Corporation (PUES), Japan, and the University of Indonesia (UI), Indonesia, are central to this project. A DC powered e-car, e-boat (Figure 2), and portable emergency power source using a novel swappable battery energy storage system were co-developed with OIST and PUES. The swappable batteries used in these e-mobility solutions are supplied primarily by energy from a new 6.2 kW rooftop solar PV system coupled with an 8 kWh battery energy storage system (BESS). The microgrid energy resources, with minimal grid power during peak demand times supply DC lighting, DC air conditioning, refrigeration, EV charging, and building critical loads within the microgrid.

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

Project Status/Results: The e-boat and e-car solutions are operational and under test and evaluation by HNEI Grid*START*. All required electrical equipment was procured, and a dedicated electrical room was built to house all newly installed switches, breakers, controls, a battery energy storage system, DC-DC converters, wiring, and other essential electrical components. The 6.2 kW rooftop solar PV system and 8 kWh BESS are fully integrated for operation within the DC microgrid. Commissioning of the full DC microgrid systems is well underway, with all except the last of five phases (the installation and testing of the microgrid controller) now complete.

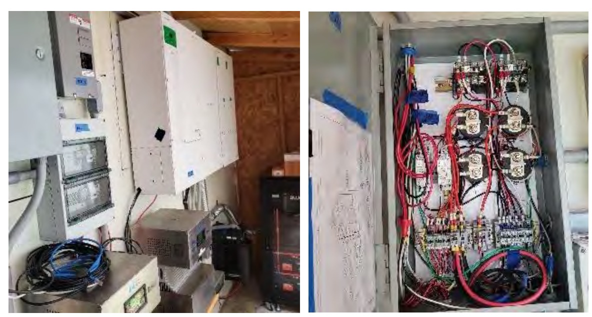

Figure 3. View of project electrical room and one of four control boxes with high voltage switches.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2022

B2: Advanced Conservation Voltage Reduction Development & Demonstration

OBJECTIVE AND SIGNIFICANCE: HNEI's Grid System Technologies Advanced Research Team (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. The main principle of CVR is that customer energy use and peak demand can be seamlessly reduced by effectively lowering the operating voltage within the acceptable operating band on distribution circuits serving customer loads.

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

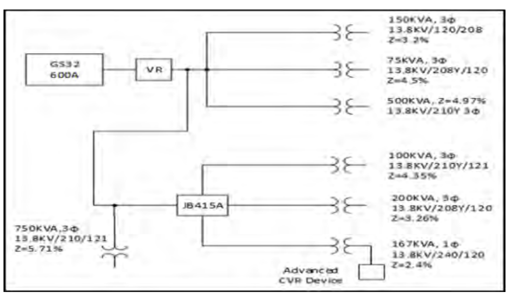

Figure 1. CVR demonstration single-line diagram.

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

PROJECT STATUS/RESULTS: Testing and validation of Grid*START*'s CVR control algorithm was completed utilizing HNEI's hardware-in-the-loop laboratory platform. Multiday real-time HIL simulations were completed using project site field voltage data under a full range of load conditions to ensure robust and reliable operation of the autonomous controller and algorithm.

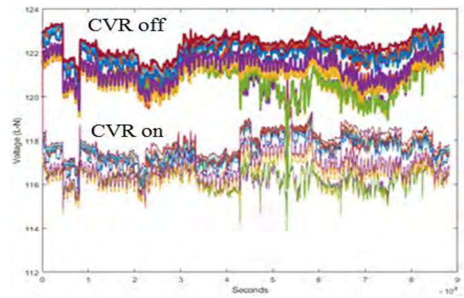

Figure 2. Voltage Profiles with CVR on and off.

Navy Seabees provided substantial project support by completing all project civil/structural work. HNEI Grid*START* installed a 5.8kW rooftop PV system and all CVR system components just prior to Japan's enactment of its COVID-19 travel entry ban. In March 2022, the project team was finally able to reenter Japan to prepare the CVR system for test and commissioning. Upon completing several system component repairs, the system was successfully commissioned in May 2022. Recently, the USMC Camp Butler team upgraded the existing base AMI communications network, improving its reliability. In turn, this has improved CVR system performance due to its reliance on the base AMI network. Following the removal of COVID-19 travel entry restrictions to Japan in October 2022, HNEI conducted further field verification tests and collected CVR system operational performance data. Preliminary analysis of CVR system performance is currently underway.


Figure 3. Project construction and new PV system.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2022

B3: Energy Generation and Resilience Opportunities Assessment for MCBH

OBJECTIVE AND SIGNIFICANCE: HNEI completed an assessment of energy generation and resilience opportunities ("EG&R Assessment") for Marine Corps Base Hawaiʻi (MCBH) (Figure 1). This study sought to identify and evaluate needs and opportunities for implementing cost-effective and commercially proven microgrid technologies (e.g., solar photovoltaics (PV), battery energy storage systems (BESS) and back-up diesel generation) on MCBH, while concurrently meeting MCBH's 14-day resiliency requirement.

Figure 1. Aerial View of MCBH at Kāneʻohe Bay.

BACKGROUND: On May 30, 2018, the Office of the Assistant Secretary of Defense Energy, Installations, and Environment (OASD-EI&E) issued the memorandum, "Installation Energy Plans – Energy Resilience and Cybersecurity Update and Expansion of the Requirement to All DoD Installations," mandating that an Installation Energy and Security Plan (IESP) be prepared for MCBH. HNEI was initially assisting MCBH with the development and completion of MCBH's IESP and delivered a preliminary draft of the report in October 2020.

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

PROJECT STATUS/RESULTS: After completing a preliminary analysis of the existing MCBH electrical infrastructure and loads in 2020, HNEI conducted a techno-economic analyses utilizing the proprietary *XENDEE Microgrid Decision Support System*, evaluating optimized long-term hybrid microgrid solutions incorporating both existing and new on-base PV generation, BESS resources, and back-up diesel generation.

Alternative microgrid designs have been proposed, developed, and assessed including microgrid solutions that range from powering the entire base (Figure 2), to smaller footprint microgrids that maintain power to each of the several base primary substations. Additionally, HNEI has analyzed the feasibility of microgrids at a more granular distribution feeder level – including at the request of MCBH leadership, an assessment of the potential for microgrid development cost reduction opportunities by the use of existing rooftop PV systems and emergency generation assets already in place at critical load centers on the base.

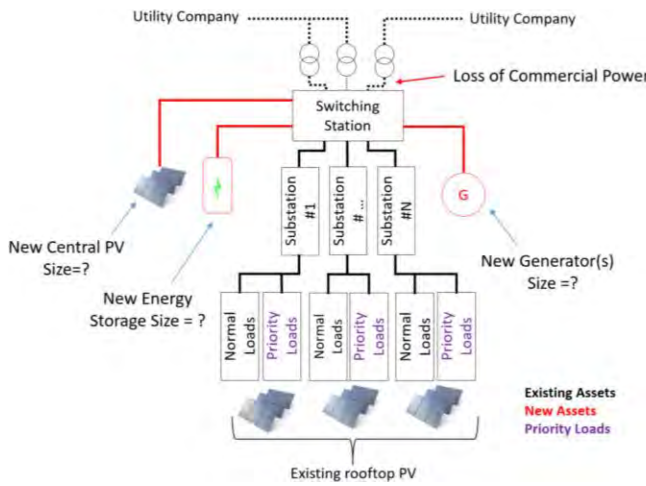

Figure 2. Conceptual Design of a Full-Base Microgrid.

HNEI delivered a draft EG&R Assessment report to MCBH in February 2022 that provided a technical and financial analysis to support the base's command to make decisions on future projects considering the base's renewable energy targets and resilience requirements. HNEI submitted its final version of the report to MCBH in July 2022.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2022

B4: Hawaiʻi Virtual Power Plant (Hi-VPP) Demonstration

OBJECTIVE AND SIGNIFICANCE: HNEI's Grid System Technologies Advanced Research Team (Grid*START*) has developed the Hawaiʻi Virtual Power Plant Demonstration Project (Hi-VPP) which aims to quantify the economic value and operational effectiveness of customer-sited battery and solar (BESS+PV) resources to simultaneously provide services to 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, the optimization of multiple services under BESS control, and the functional tradeoffs between simple, low-bandwidth and advanced, highly coordinated methods of VPP aggregation. Ultimately, it will help better quantify the business case for VPPs, including the value proposition for customer participation in a VPP and utility utilization of the same.

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

Figure 1. Sunverge SIS BESS + PV units.

PROJECT STATUS/RESULTS: HNEI Grid*START* deployed four Advanced Real-Time Grid Energy Monitor System (ARGEMS) devices at the demonstration site. These meters measure behind-the-meter (BTM) loads in order to optimize the charge/discharge schedule of BESS units. Also, HNEI Grid*START* refined the optimization function and developed an application programming interface (API) to monitor and control all battery units.

Figure 2. Load measurement box with ARGEMS devices.

Based on research of various grid services and value streams for the Hawaiʻi market, a baseline optimization problem was formulated. Then, a control algorithm was developed to find the optimal values for customers to participate in VPP programs, making significant progress in the formulation, implementation, and control application of the underlying economic optimization. Numerous simulations have been conducted to demonstrate the economic benefits of customers when participating in VPP-based grid service programs.

HNEI Grid*START* will continue to develop control algorithms, establish a control management system, and evaluate the performance of the updated system.

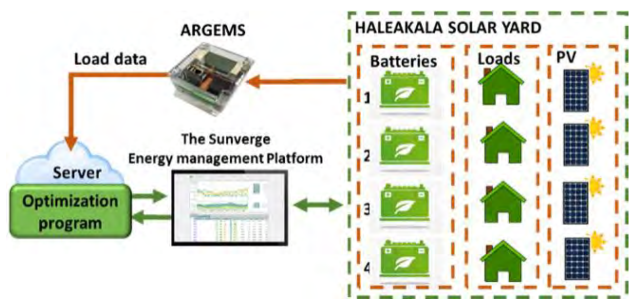

Figure 3. Data flow overview.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2022

B5: Bidirectional EV Charging Demonstration Project

<u>OBJECTIVE AND SIGNIFICANCE</u>: 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 help 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. The methodologies developed under this project will be applicable elsewhere.

<u>BACKGROUND</u>: HNEI Grid*START* is collaborating with IKS Co., Ltd. (IKS) on technology development, test, and demonstration of advanced control of two bidirectional electric vehicle (EV) chargers (H-PCSs) 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 an HNEI Grid*START* developed secure web-based car scheduling application.

The novel H-PCS control algorithms developed by HNEI Grid*START* first ensure 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 (i.e., Hawaiian Electric Company) through the supply of grid ancillary services in return for financial compensation.

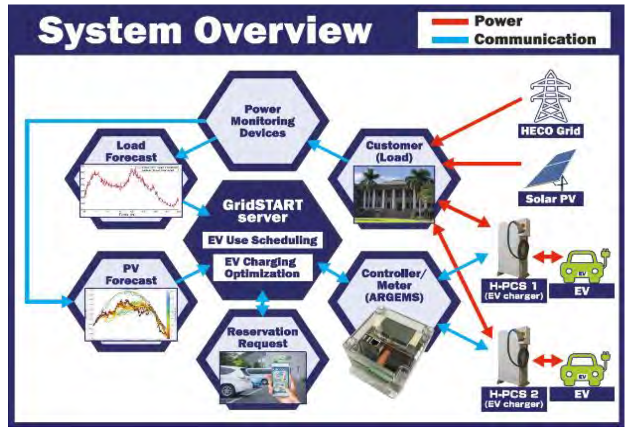

Figure 2. Functional system diagram.

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.

<u>PROJECT STATUS/RESULTS</u>: HNEI Grid*START* has completed the installation and connection of the two EV chargers to the campus power grid. The custom web-based reservation software was integrated with the autonomous control algorithms and deployed on the project's dedicated server. In September 2022, the project was introduced with multiple sessions of in-person user training to all HNEI employees and additional drivers from select UHM administrative departments. The system (EV chargers, EVs, and reservation program) is now open for daily use. The system performance and economic value of the EV charge/discharge optimization algorithm is now under test, with performance monitoring, data collection, and analysis by HNEI researchers underway.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2022

B6: Development and Verification of AI-Based Microgrid Platform and Business Model

OBJECTIVE AND SIGNIFICANCE: The goal of this project is to demonstrate the capabilities of an advanced control system using artificial intelligence (AI) to optimize energy management of a distributed solar and energy storage based microgrid to reduce costs, and improve resilience of the seawater distribution system at the Hawai‘i Ocean Energy, Science & Technology (HOST) Park. The microgrid control system has been designed with the potential capability to provide energy management across the entire 900-acre HOST Park where more than 40 companies operate business/pilot sites.

BACKGROUND: HOST Park is a unique outdoor demonstration site for renewable energy, aquaculture and other ocean-based sustainable technologies. The demonstration site is in a section of the Park that includes three sets of pipelines capable of delivering up to 100,000 gallons per minute of cold seawater from depths of 3,000 ft. The innovative green economic development park is administered by the Natural Energy Laboratory of Hawai‘i Authority (NELHA), an agency of the State of Hawai‘i. Interruptions in electrical service have the potential to irreparably damage the businesses that depend on the seawater for their agricultural and production requirements. The proposed microgrid, with AI capability, is intended to reduce utility costs and reduce or eliminate outages of the seawater pumping system.

The Hawai‘i Natural Energy Institute (HNEI) conceived the project, initiated efforts to apply for Korea Institute of Energy Technology, Evaluation and Planning (KETEP) grant funding, and helped form the consortium of United States and Korean participants. In 2018, KETEP awarded the project team a grant of KrW 1,940 million, approximately USD 1.73 million via the Korea Ministry of Trade, Industry, and Energy as part of their International Energy Collaborative Research and Development Program. The project entails a detailed design, deployment, testing, and evaluation of an AI microgrid that includes photovoltaic panels and battery energy storage systems at the HOST Park.

PROJECT STATUS/RESULTS: HNEI supports the microgrid development project by advising on requirements for grid interconnection between the proposed HOST Park microgrid and the Hawai‘i Electric Light Company (HELCO) grid, including 1) the potential applicability and impacts of microgrid service tariffs; 2) functional requirements and use cases for the microgrid; and 3) project team engagement with the engineering, procurement and construction (EPC) and financial contractors.

During 2022, microgrid construction began with clearing of the lava fields and installation of ground-mounted PV array. The battery energy storage system is expected to be installed by end of year, with the microgrid operational by March 31, 2023.

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

- 2021, W-H. Park, H. Abunima, M.B. Glick, Y-S. Kim, **Energy Curtailment Scheduling MILP Formulation for an Islanded Microgrid with High Penetration of Renewable Energy**, Energies, Vol. 14, Issue 19, Paper 6038.
- 2020, R-K. Kim, M.B. Glick, K.R. Olson, Y-S. Kim, **MILP-PSO Combined Optimization Algorithm for an Islanded Microgrid Scheduling with Detailed Battery ESS Efficiency Model and Policy Considerations**, Energies, Vol. 13, Issue 8, Paper 1898.
- 2019, J-W. Chang, G-S. Lee, H-J. Moon, M.B. Glick, S-I. Moon, **Coordinated Frequency and State-of-Charge Control with Multi-Battery Energy Storage Systems and Diesel Generators in an Isolated Microgrid**, Energies, Vol. 12, Issue 9, Paper 1614.

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

Contact: Mark B. Glick, mbglick@hawaii.edu

Last Updated: November 2022

C1: Sustainable Aviation Fuel Production

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

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

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

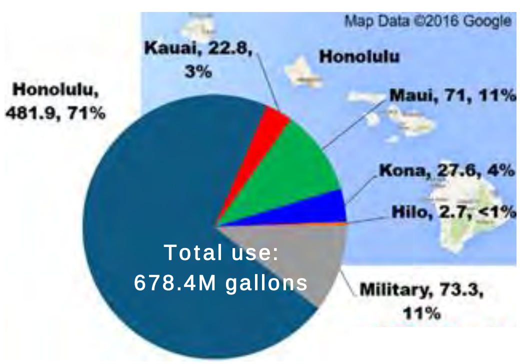

Figure 1. Commercial and military jet fuel use in 2015.

PROJECT STATUS/RESULTS: Literature reviews of both biomass feedstocks and their behavior in SAF conversion processes have been completed and published. Based on stakeholder input, barriers to SAF value chain development in Hawai‘i have been identified and reported. Technical estimates of land resources that can support agricultural and forestry-based production of SAF feedstocks have been completed using GIS analysis techniques. Samples from Honolulu's urban waste streams and candidate agricultural and forestry feedstocks have been collected and subjected to physicochemical property analyses to inform technology selection and design of SAF production facilities.

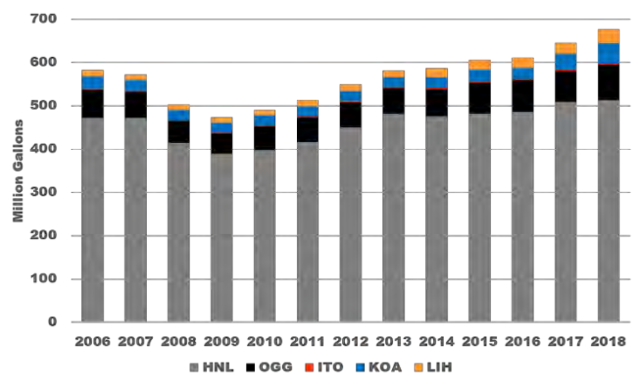

Figure 2. Commercial jet fuel consumption in Hawai‘i.

Fuel Properties of Construction and Demolition Waste Streams

A sampling and analysis campaign was undertaken to characterize fuel properties of construction and demolition waste (CDW) streams on O‘ahu. 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 *Frontiers in Energy Research*. 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). Summaries of test results are under review.

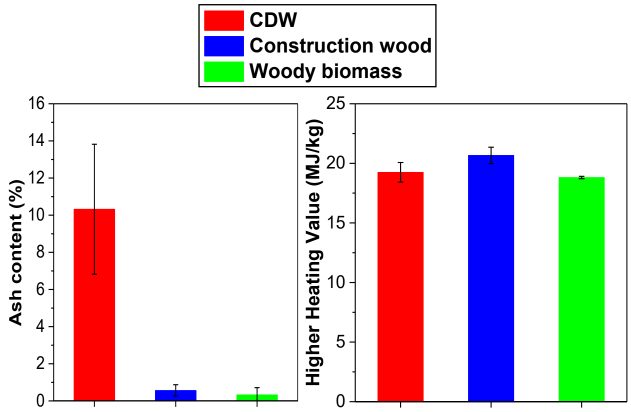

Figure 3. Ash content (left) and heating value (right) of the combustible fraction of CDW compared to construction wood and woody biomass.

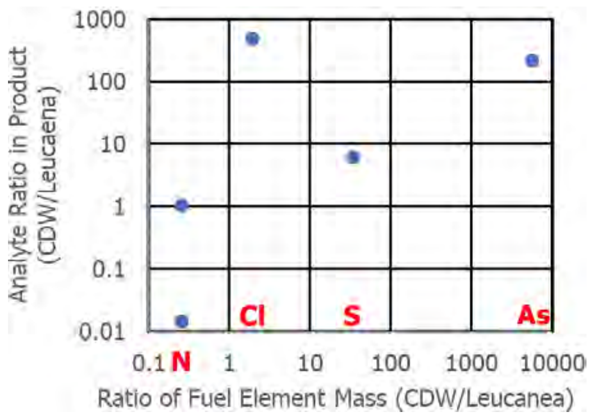

Figure 4. Relative ratios of elements in present in fuels to ratios in the product gas stream.

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/partners;
- Continued stakeholder engagement;
- Acquiring transportation network and other regional data;
- Evaluating infrastructure availability; and
- Evaluating feedstock availability.

Exploration of Biomass Feedstocks for Hawai'i

Figure 5 shows the breakdown of land use of the nearly 2 million acres of agricultural lands in Hawai'i. With the shuttering of much of the cane sugar and the pineapple industries, this total has dropped further. Bringing agricultural lands back into production can support diversification of the economy and support rural development. Biomass feedstocks for sustainable aviation fuel production are options that can contribute to this revitalization. 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 *Energy and Fuels*.

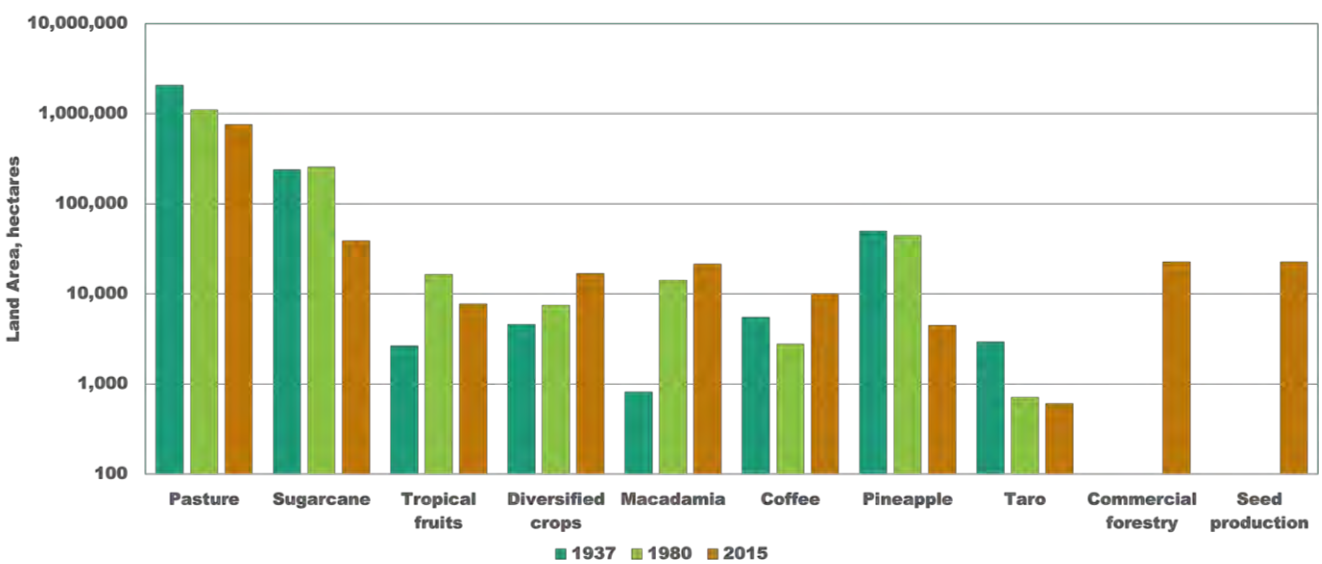

Figure 5. Breakdown of agricultural land use in Hawai'i; in 2015, approximately 100,000 acres were harvested.

The Eco Crop 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 Eco Crop 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 technical potential estimates. A report detailing these results is being drafted.

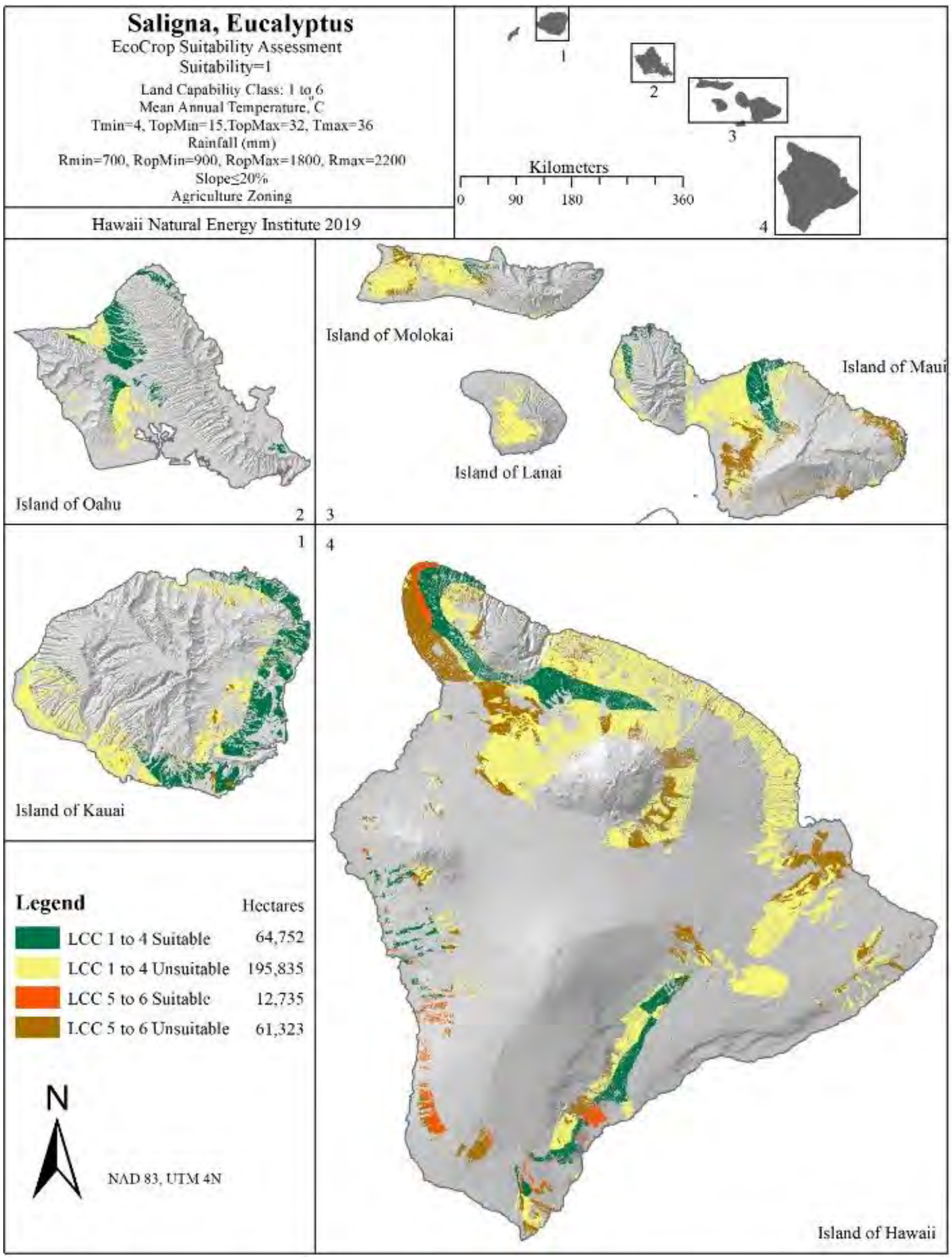

Figure 6. EcoCrop assessment of Saligna, Eucalyptus.

Evaluation of Pongamia

Of the sustainable aviation fuels currently approved by ASTM and the FAA, those based on the use of oils derived from plants and animals have the highest SAF yield and the lowest production costs.

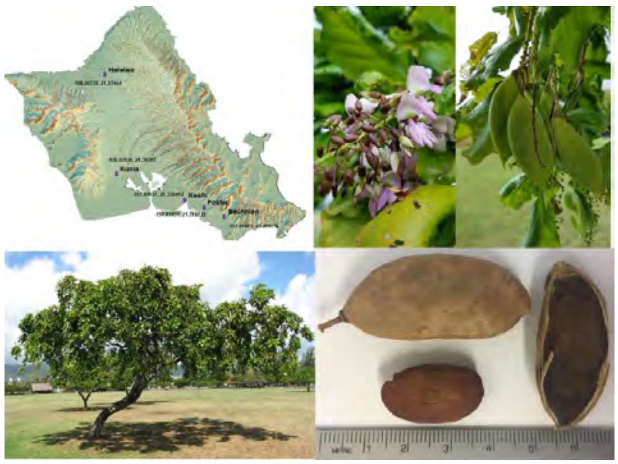

Figure 7. Locations and images of Pongamia.

Invasiveness Assessment

Pongamia (*Millettia pinnata*) (Figure 7) is a tree, native to the tropics, that bears an oil seed and has plantings established on O'ahu. Under this project, an observational field assessment of trees in seven locations on O'ahu was conducted by Professor Curtis Daehler (UH Dept. of Botany) to look for direct evidence of pongamia escaping from plantings and becoming an invasive weed. Although some pongamia seedlings were found in the vicinity of some pongamia plantings, particularly in wetter, partly shaded environments, almost all observed seedlings were restricted to areas directly beneath the canopy of mother trees. This finding suggests a lack of effective seed dispersal away from pongamia plantings. Based on its current behavior in the field, pongamia is not invasive or established outside of cultivation on O'ahu. Because of its limited seed dispersal and low rates of seedling establishment beyond the canopy, risk of pongamia becoming invasive can be mitigated through monitoring and targeted control of any rare escapes in the vicinity of plantings. Seeds and seed pods are water dispersed, so future risks of pongamia escape and unwanted spread would be minimized by avoiding planting at sites near flowing water, near areas exposed to tides, or on or near steep slopes. Vegetative spread by root suckers was not observed around plantings on O'ahu, but based on reports from elsewhere, monitoring for vegetative spread around plantations is recommended; unwanted vegetative spread might become a concern in the future that could be addressed with localized mechanical or chemical control. A detailed technical report "***Observational Field Assessment of Invasiveness of Pongamia (Millettia pinnata), A Candidate Biofuel Crop in Hawai'i***" summarized this work.

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 8). 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 *ACS Omega*.

Figure 8. Pathways from Pongamia seed pods to fuel.

Coproduct Development
Additional studies were devoted to developing coproducts from pongamia pods. Leaching and torrefaction experiments were performed to remove inorganic constituents and reduce the oxygen content of the pods (Figure 9). 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**" in *Fuel* respectively.

Figure 9. 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. Preliminary studies found the oil content of the kukui nuts is ~60% wt, which is ~20-30% wt higher than that of pongamia seeds and kamani nuts. The unsaturated fatty acids, however, accounted for ~90 % wt of the kukui nut oil, slightly higher than that of kamani nut (~75% wt) and pongamia seed oil. Kukui and kamani nut oil are different from the pongamia seed oil, in that the primary fatty acid is linoleic acid (C18:2).

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

Contact: Scott Turn, sturn@hawaii.edu

Last Updated: November 2022

C2: 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 the 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: 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. 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[3]. An estimation also reported that ~8.5 billion tons of waste materials could be mined from the existing U.S. landfills[4].

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.

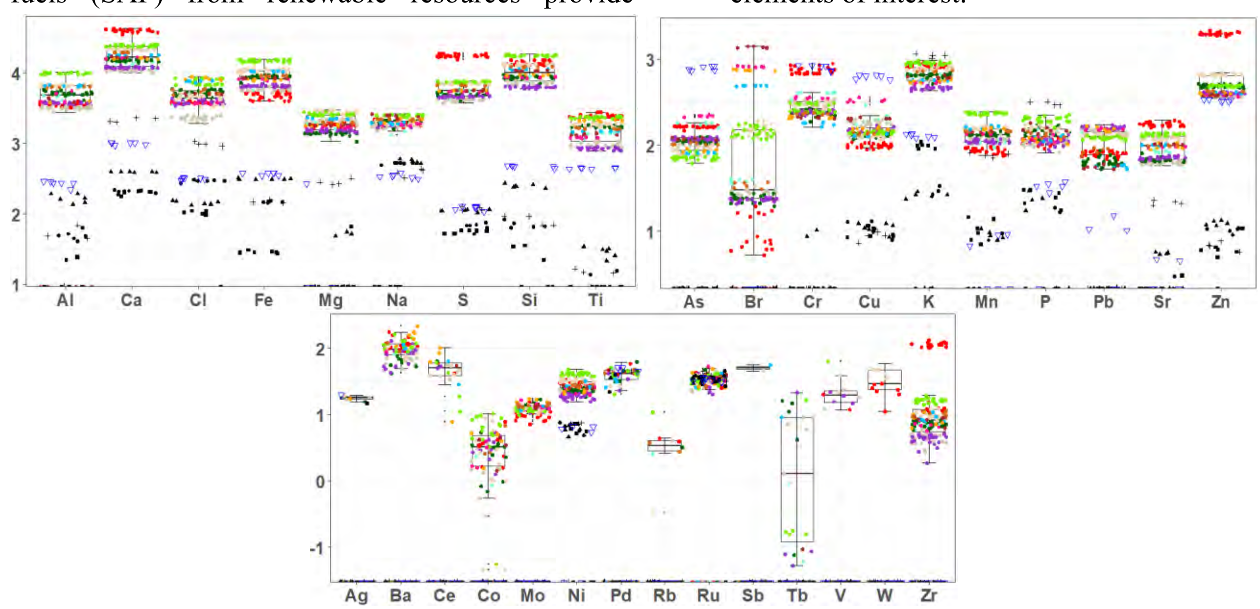

Figure 1. Element concentrations (log10 of ppm) in 12 CDW samples and five reference material samples.

[3] 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.

[4] 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.

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[5]. 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.
- Strategies to control and/or remove gas phase inorganic species (e.g. As) from product gas using sorbents.

A number of these FactSage calculations at different gasification conditions are plotted on the following page (Figure 2).

Funding Source: DLA Energy.

Contact: Scott Turn, sturn@hawaii.edu

Last Updated: November 2022

[5] 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.

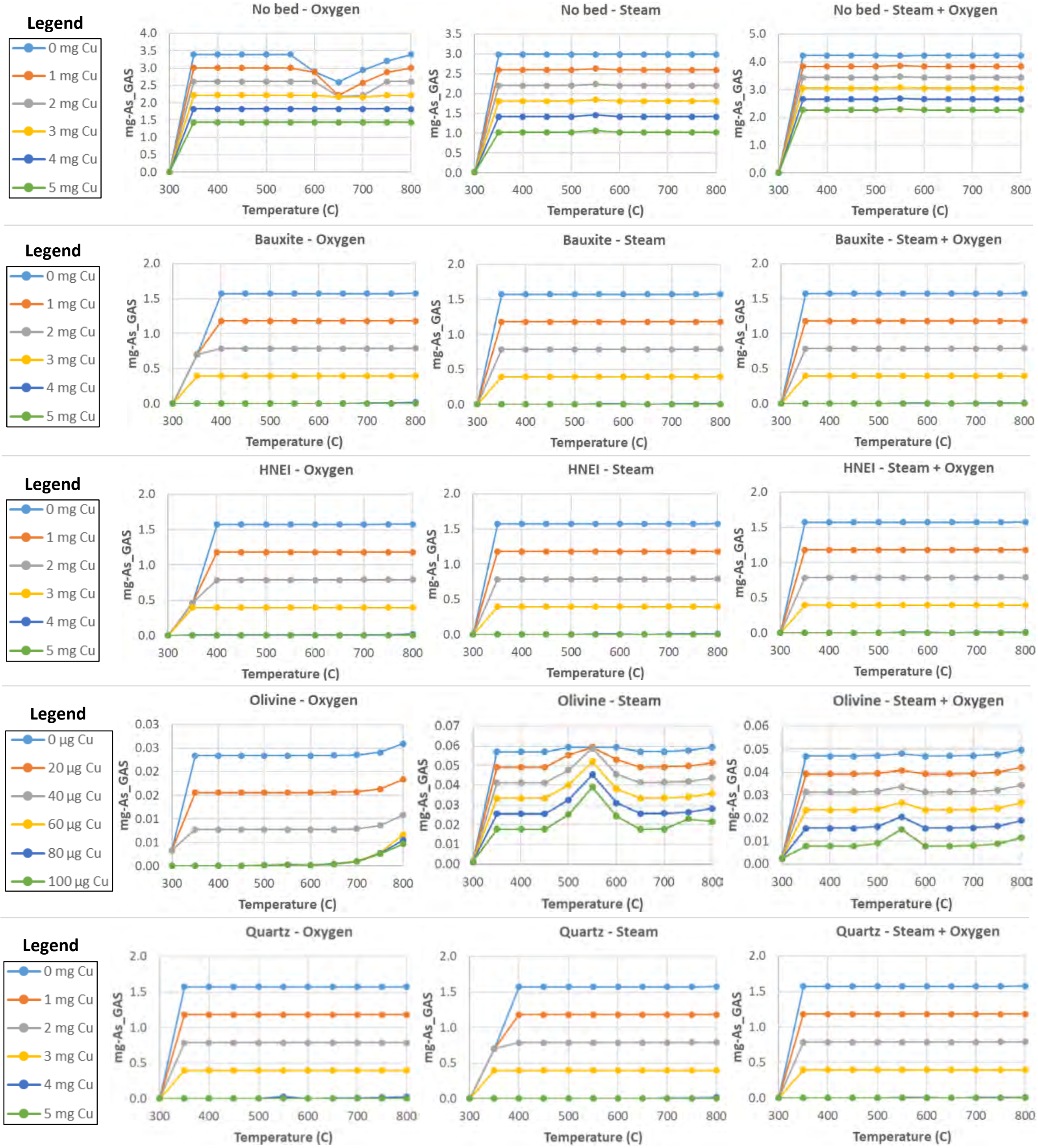

Figure 2. Masses (in milligram) of arsenic in gas phase from the FactSage calculations at different gasification conditions (bed materials: No-Bed, Bauxite, HNEI, Olivine, Quartz; and oxidizer: Oxygen, Steam, and Steam+Oxygen) and sorbent conditions. Copper masses are (µg Cu in sorbent per 100 g of fuel) for Olivine bed and (mg Cu in sorbent per 100 g of fuel) for other bed materials.

C3: Fuel Characterization by Multidimensional Gas Chromatography

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to identify and characterize trace quantities of heteroatomic organic species (HOS) in aviation, maritime, and diesel fuels. New analytical methods under development can evaluate the composition of fuels currently in use and those stored as strategic reserves and investigate the impacts of crucial nitrogen and sulfur containing compounds and additives on fuel properties. Comprehensive fuel composition information can be further employed to replace costly experimental measurements by calculating various physicochemical properties of fuel. The knowledge gained in this project will improve the understanding of the influences of HOS and fuel additive deterioration on fuel stability and physicochemical properties, guide efforts to preserve fuel quality, and reduce the cost of fuel characterization.

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

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

A 2D-GC was acquired in August 2018, expanding the fuel laboratory’s ability to identify and quantify fuel constituents present in trace amounts (≤100 ppm). The HNEI 2D-GC employs two injectors and three detectors (i.e. mass spectrometer, nitrogen chemiluminescence and sulfur chemiluminescence) to analyze fuel components and HOS with a single injection event. Neat fuels can be injected directly without requiring solvent dilution. Quantum chemical software based on the conductor-like screening model for realistic solvation (COSMO-RS) method was employed to calculate the physicochemical properties of petroleum and sustainable aviation fuels based on their individual 2D-GC compositions.

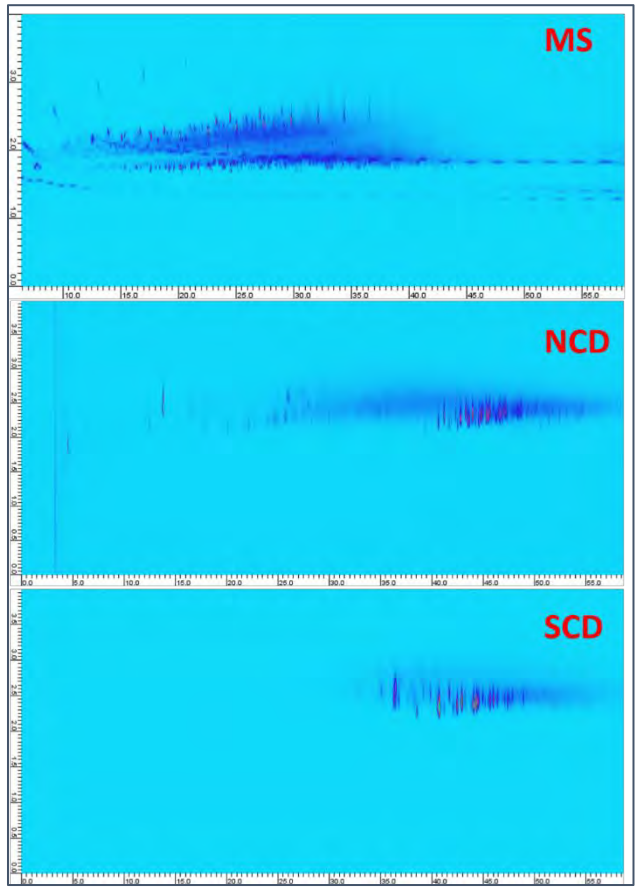

Figure 1. Comprehensive 2D-GC analysis of F-76 diesel fuel with MS, NCD, and SCD.

PROJECT STATUS/RESULTS: HNEI is currently collaborating with personnel from the U.S. Navy Fuels Cross-Functional Team at Naval Air Station Patuxent River (Pax River) on 2D-GC applications.

Past activities under this project included 1) participation in round robin tests on nitrogen compounds in various type of fuels, 2) determining the impacts of dissolved water on the fuel low temperature qualities, and 3) prediction of water solubility in fuels based on their individual 2D-GC compositions and COSMO-RS.

Currently, HNEI's activities include:

- Determining fuel hydrocarbon matrix;
- Exploring the influences of sulfur and nitrogen containing compounds on the degradation of fuel antioxidants and the consequent impacts on fuel stabilities;
- Utilizing HOS characterization methods to investigate the potential impacts of HOS on fuel properties and fuel stability;
- 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.

This project has produced the following paper:

- 2023, J. Fu, **Dissolved water in jet fuels: a low-temperature quality and water solubility study**, Fuel, Vol. 331, Part 2, Paper 125950.

Funding Source: Office of Naval Research

Contact: Scott Turn, sturn@hawaii.edu;
Jinxia Fu, jinxiafu@hawaii.edu

Last Updated: November 2022

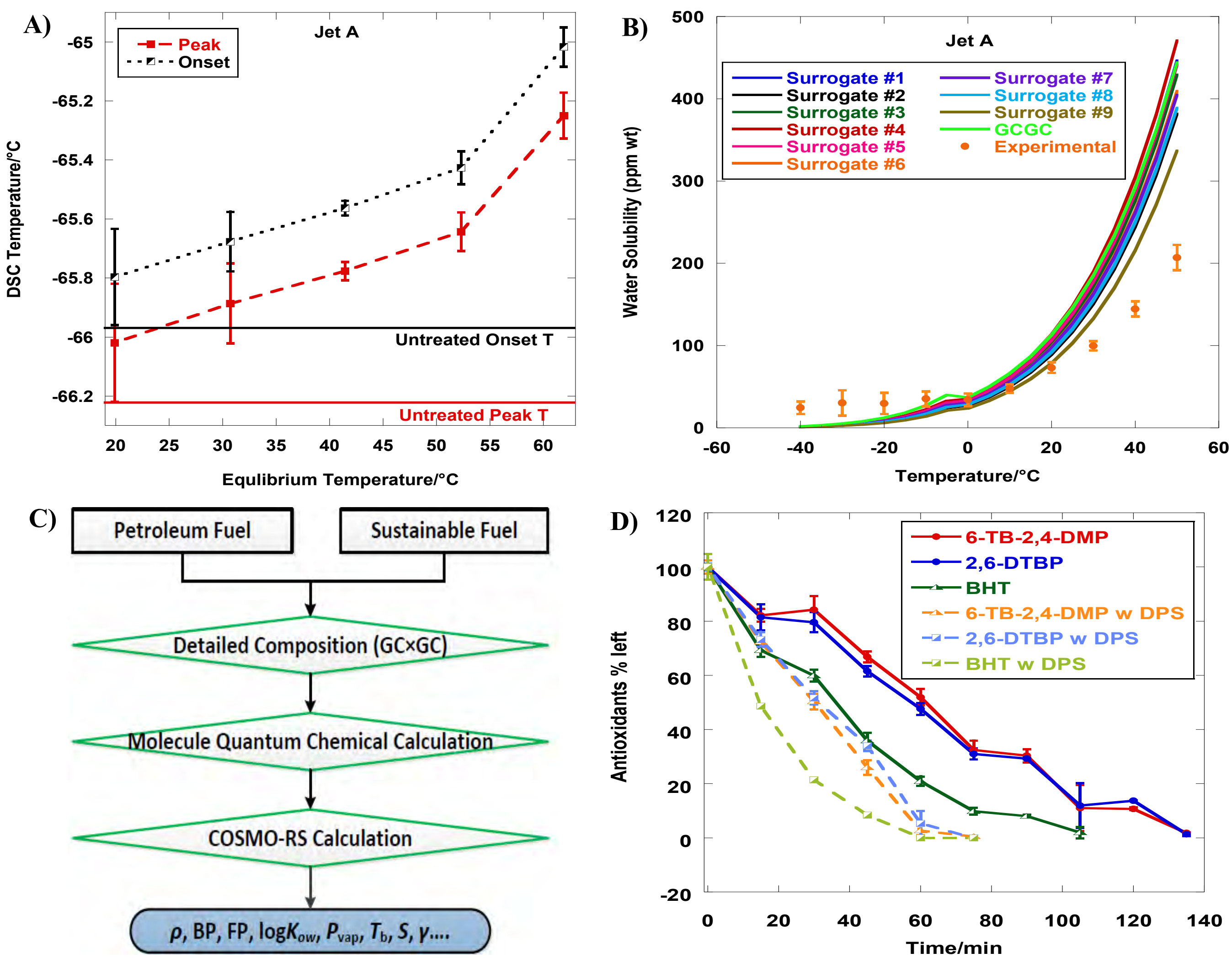

Figure 2. (A) DSC onset and peak temperatures versus water vapor-fuel equilibrium temperature of Jet A; (B) water solubility in Jet A calculated by COSMO-RS vs. experimental values; (C) schematic of COSMO-RS fuel property calculation; (D) impacts of diphenyl sulfide (DPS) on the degradation of 3 fuel antioxidants, i.e. 6-tert-butyl-2,4-dimethylphenol (6-TB-2,4-DMP), 2,6-di-tert-butylphenol (2,6-DTBP), and 2,6-di-tert-butyl-4-methylphenol (BHT).

C4: Novel Biocarbons

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

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

PROJECT STATUS/RESULTS: Experiments at controlled reactor pressures were completed to better understand pressure's role in TPP biocarbon formation. These parametric tests provided preliminary data needed to design a factorial experimental campaign to identify control variable interactions. Variables available to control reaction conditions include temperature, pressure, particle size, moisture content, bulk density, reactant gases, and reaction time, etc. These findings may enable biomass utilization as feedstock to displace fossil carbon products, with application as metallurgical reductants, binders, electrodes, or high value specialty materials.

Figure 1. Transient plastic phase biocarbons.

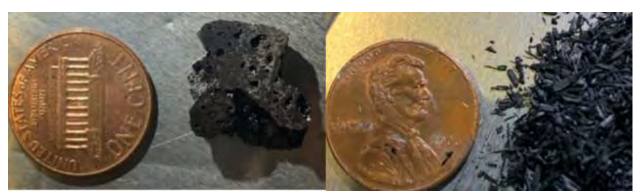

Figure 2. Transient plastic phase biocarbon (left) and non-transient plastic phase biocarbon on (right). Both products made from the same biomass feedstock.

Funding Source: SINTEF Energy Research; Office of Naval Research

Contact: Scott Turn, sturn@hawaii.edu

Last Updated: November 2022

Hawai‘i Natural Energy Institute Research Highlights

Appendix C: Alternative Fuels

C5: Solar Fuels Generation

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

BACKGROUND: 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 (typically a strong acid) and solar fuels are generated directly at its surface. Fuels produced with this method can be stored, distributed, and finally recombined in a fuel cell to generate electricity, with water as the only byproduct.

In 2017, the team at HNEI's Thin Films Laboratory teamed up with several national laboratories (LLNL, LBNL, and NREL) and mainland academic teams (Stanford, UNLV) to develop new semiconducting materials for PEC water splitting, with primary focus on *chalcopyrites*. This material class, typically identified by its most popular PV-grade alloy $CuInGaSe_2$, provides exceptionally good candidates for PEC water splitting. A key asset of this thin-film semiconductor material class is its outstanding power conversion efficiency, as demonstrated with $CuInGaSe_2$-based PV cells (>23%). In a PEC configuration, our group has demonstrated that chalcopyrite-based systems are also efficient at storing solar energy into hydrogen bonds without the need of expensive precious catalysts (Gaillard, 2013).

PROJECT STATUS/RESULTS: HNEI's Thin Films Laboratory is now combining theoretical modeling with state-of-the-art materials synthesis and advanced characterization capabilities to provide deeper understanding of *chalcopyrite*-based PEC materials and engineer high-performance devices. For example, the HNEI team collaborated with Stanford and UNLV to develop coatings for prolonged PEC operations. We demonstrated that molybdenum disulfide (MoS_2) films only few atoms thick could effectively protect cadmium sulfide (CdS) in acid for 7 hours, whereas unprotected CdS samples dissolved instantly (Hellstern, 2019). Likewise, we reported that tungsten oxide (WO_3) could increase the stability of copper gallium selenide ($CuGaSe_2$) in acid by a factor of 2 when compared to un-coated samples (Palm, 2020).

The HNEI team also partnered with LLNL and UNLV to discover novel PEC materials. Theoreticians at LLNL used an algorithm to determine the chemical composition a material should possess to meet specific optoelectronic properties. At HNEI, the team synthesized specimens following LLNL's theoretical calculations. Then, the fundamental properties of the newly formed materials were measured at UNLV. Experimental data were finally fed back into LLNL's model to refine its prediction. Using this theory-synthesis-characterization feedback loop, a novel class of absorbers known as *ordered vacancy compounds* was successfully fabricated (Gaillard, 2021).

The listed publications are linked on the following page.

Funding Source: Department of Energy

Contact: Nicolas Gaillard, ngaillar@hawaii.edu

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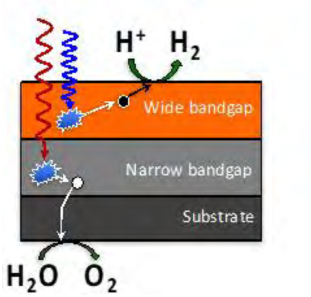
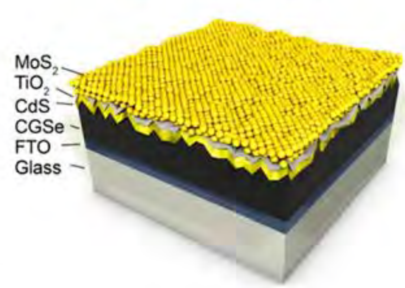
Photoelectrochemical device concept



Color tunable chalcopyrite solar absorbers

Ultra thin corrosion protection layers



ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

1. 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.
2. 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.
3. 2019, T.R. Hellstern, D.W. Palm, J. Carter, A.D. DeAngelis, K. Horsley, L. Weinhardt, W. Yang, M. Blum, N. Gaillard, C. Heske, T.F. Jaramillo, **Molybdenum Disulfide Catalytic Coatings via Atomic Layer Deposition for Solar Hydrogen Production from Copper Gallium Diselenide Photocathodes**, ACS Applied Energy Materials, Vol. 2, Issue 2, pp. 1060-1066.
4. 2013, N. Gaillard, D. Prasher, J. Kaneshiro, S. Mallory, M. Chong, **Development of Chalcogenide Thin Film Materials for Photoelectrochemical Hydrogen Production**, Proceeding of the MRS Spring Meeting, MRS Proceedings, Vol. 1558, Paper mrss13-1558-z02-07.

D1: 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) compared to similar vehicles powered by high energy lithium batteries. Contaminants in the air, in the fuel, and from system materials can limit the use of fuel cells in these applications. Contamination problems can be compounded by the reaction products that impact many key fuel cell materials. Under this task, HNEI continued support to the Naval Research Laboratory's (NRL) efforts to develop lightweight, high efficiency fuel cell systems for UAVs and continued efforts to enhance contaminant tolerance.

BACKGROUND: Electric propulsion offers several advantages over small hydrocarbon powered engines for unmanned vehicles, i.e. near silent operation, instant starting, increased reliability, easier power control, reduced thermal signature, reduced vibration, and no electric generators. A partnership between HNEI and NRL was established in 2009 to aid in NRL's development of the IonTiger UAV using a fuel cell made by an outside vendor. 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 PEMFC 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) PEMFCs for transportation and unmanned vehicle applications. High temperature (140-200° C) PEMFCs have the benefits of higher contaminant tolerance and lower cost membranes vs. low temperature PEMFCs. 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).

PROJECT STATUS/RESULTS: HNEI is replicating 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 (PEMs), and electrode structures designed for use in next-generation contaminant resistant fuel cells for UAVs.

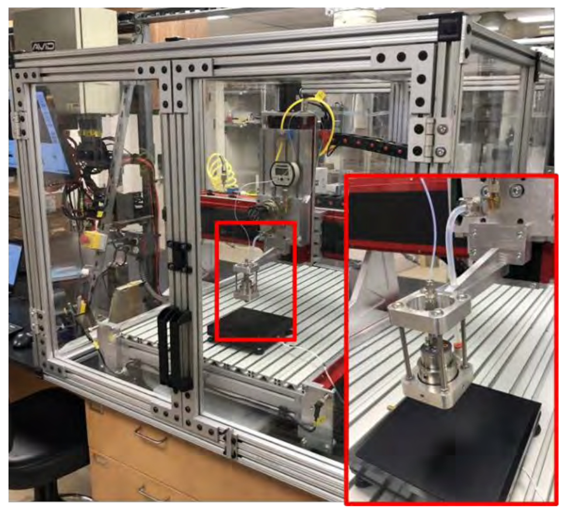


Figure 1. Ultrasonic spray coating system for in-house manufacturing of custom CCMs.

HNEI has established capabilities to manufacture membrane electrode assemblies in-house to support the development of high temperature PEM components.

This project has produced a number of works listed on the following page.

Funding Source: Office of Naval Research

Contact: Keith Bethune, bethune@hawaii.edu

Last Updated: November 2022

ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

5. 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.
6. 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**)
7. 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, Hawai‘i, 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.

D2: Proton Exchange Membrane Fuel Cell Contamination

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

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

In past decades, PEMFC contaminants were studied with single cells or stacks using both accelerated and long-term tests. At HNEI, more than twenty potential contaminants have been studied in single cell tests. Most of these compounds are able to adsorb and react on Pt surface and compete with oxygen reduction reaction, a key reaction in PEMFC. While the effects from both unsaturated hydrocarbon and oxygen-containing hydrocarbon contaminants, could be mitigated by interrupting the explosure to contaminants for sulfur and halogen compounds degrade cell performance that does not recover with clean air operation. The contamination also accelerates the permanent degradation of Pt catalysts and electrolyte membrane. The contamination mechanisms of those compounds (e.g. bromomethane) are illustrated in Figure 1.

The contaminants permeate through the thin ionomer film and break down to adsorbates ($BrCH_3$ to Br^-, SO_2 to S and SO_4^{2-}) on the Pt catalyst surface. The adsorbates cannot be oxidized or desorbed under normal PEMFC operating conditions, and accumulate at the catalyst-electrolyte film interface. The anions even cannot be removed by cyclic voltammetry scanning alone due to Donnan exclusion by the ionomer. The catalyst surface then loses activities to the fuel cell reactions. For a long-term operation, the absorption of anions also causes permanent damages on the MEA, such as Pt dissolution and particle growth, and ionomer electrolyte decomposition.

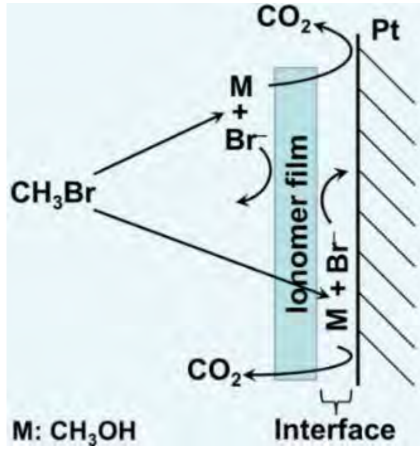


Figure 1. Contamination mechanisms of bromomethane in PEMFC cathode.

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

PROJECT STATUS/RESULTS: Under this project, HNEI has developed performance recovery techniques that, in one case incorporates a combination of purging and flushing operations; and in other cases, uses an in-situ catalytically filtration method to eliminate the contaminants before it reaches the catalysts layer. The specific procedures are based on a comprehensive understanding on the contamination mechanisms of the selected air pollutants. The recovery method validated using single cells was shown to restore the performance losses and remove the adsorbates and anions after poisoning with bromomethane, hydrogen chloride, or sulfur dioxide.

Representative results are shown in Figures 2 and 3. The cell performance was restored to 100%, 97%, and 99% of its initial value, respectively for those contaminants.

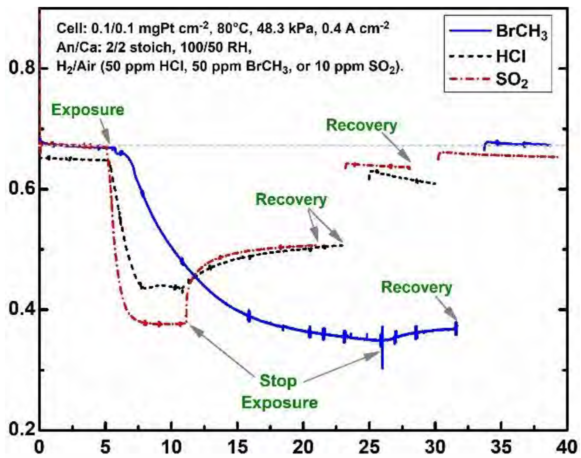
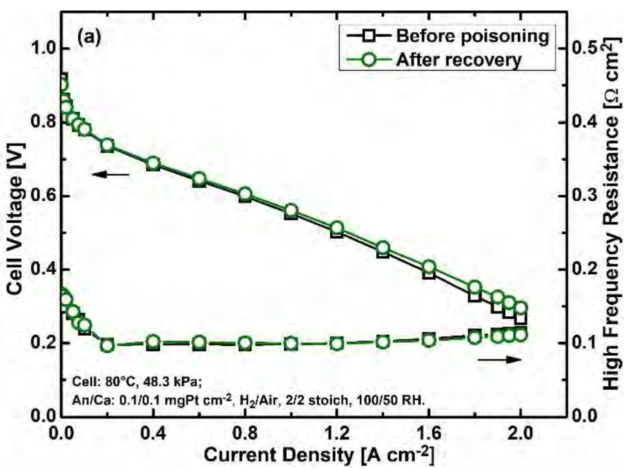
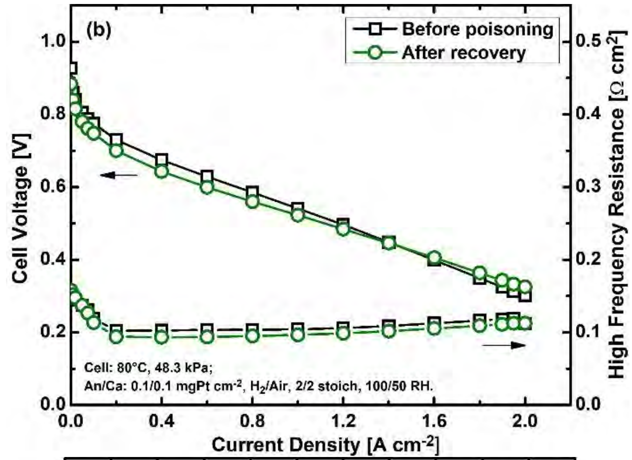


Figure 2. Cell performance responses to bromomethane, hydrogen chloride, and sulfur dioxide contamination and the subsequent recovery.





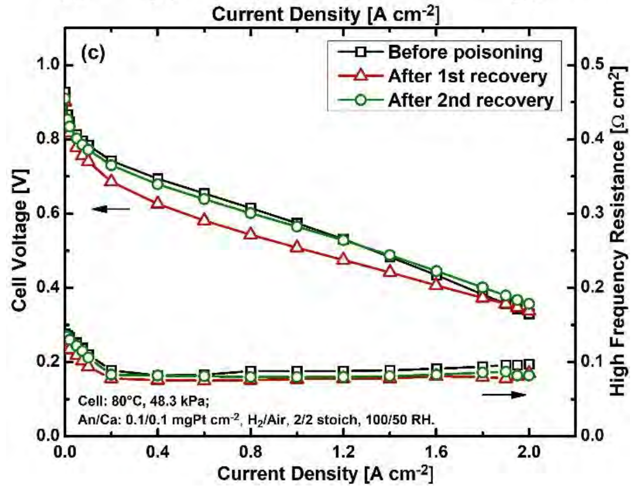


Figure 3. Cell polarization curves and high frequency resistance before poisoning and after recovery: (a) bromomethane, (b) hydrogen chloride, and (c) sulfur dioxide.

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

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

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Last Updated: November 2022

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 evaluate the performance of AEMFCs with platinum group metal (PGM) content and PGM-free cathode catalysts under various operating conditions; to study effects of membrane electrode assemblies (MEAs) components on mass transport, water management, and durability; and to 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 alkaline environment is less corrosive and can improve durability.

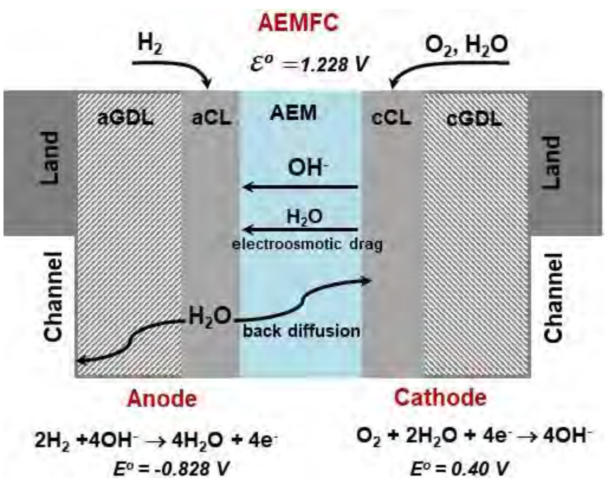

Figure 1. Schematic representation of AEMFC.

A logical step would be integration of Pt and PGM-free catalysts to the AEMFC MEA. 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. Electrochemical impedance spectroscopy (EIS) is a unique tool for fuel cells testing and characterization without interruption of operation. Analysis of impedance spectra can be performed either by spectra fitting using a relevant physics-based model, or by means of distribution of relaxation times (DRT) technique.

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

- Developed and validated code for DRT calculation of EIS (Figure 2);
- Acquired and tested a novel design of segmented cell hardware, which allowed us to evaluate not only rib-channel but also open flow field architectures for AEMFC;
- Identified AEMFC electrode design concepts to improve performance and durability; and
- Resumed partial operation of fuel cell testing facility at the University of Hawai‘i at Mānoa campus following the 2020 closure of the Hawai‘i Sustainable Energy Research Facility.

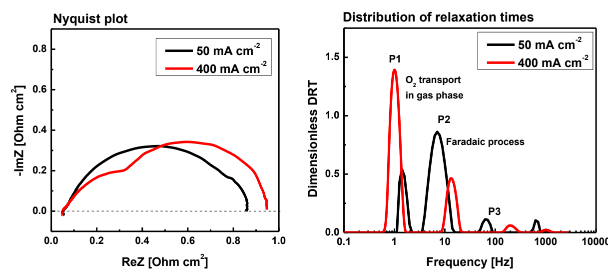

Figure 2. Nyquist plot and calculated DRT curves showing separation of mass transport and faradaic processes in fuel cell at 50 and 400 mA cm^{-2}.

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

Funding Source: Office of Naval Research

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D4: PGM-Free Catalysts for PEM Fuel Cell Applications

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

BACKGROUND: PEMFC commercial energy generated systems are typically utilizing Pt-based catalysts for hydrogen oxidation and oxygen reduction at anode and cathode, respectively. The substitution of oxygen reduction Pt catalysts by PGM-free materials lowers manufacturing cost (less than or equal to $3/kW) and ensures independence from Pt and other precious metal availability. In addition, PGM-free cathode catalysts provide tolerance to the main air-polutants like NO_2 and SO_2, which compromise Pt-based PEMFC operation. So, application of PGM-free electrocatalysts leads to production of low-cast and contaminat tolerant PEMFCs.

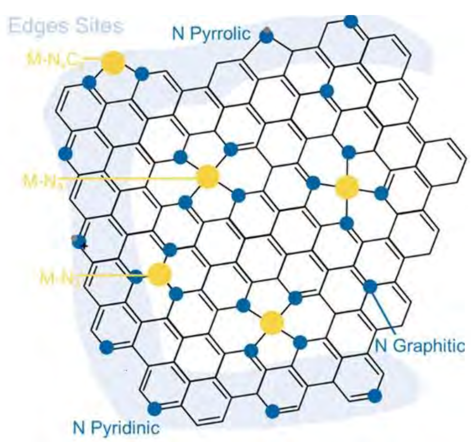

Figure 1. Schematic representation of PGM-free catalyst with M-N_x active sites[6].

PGM-free catalysts consist of non-precious transition metal (Fe, Co, Mn) coordinated by nitrogen inside a matrix of graphitic carbon (M-N-C) and can be inexpensively manufactured at scale (Figure 1). These catalysts possess high intrinsic activity for oxygen reduction measured in electrochemical half-cell configuration. However, PGM-free electrocatalysts integrated in membrane electrode assembly (MEA) demontsrtaed lower performance compared to Pt based fuel cells. Their performance can be improved by designing and optimizing the cathodic catalyst layer (CCL) and MEA construction such that: 1) it efficiently provides oxygen access to Fe-N_x active sites (through catalyst morphology control), 2) it removes water from the CL (by tuning the hydrophobicity of the PGM-free catalysts and the catalyst layer structure) and 3) it increases proton conductivity (by homogeneous mixing of catalysts and ionomer). Thus, the performance can be improved by synergistic efforts of materials design, fine tuning of the electrode layer and comprehensive electrochemical analysis.

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

PROJECT STATUS/RESULTS: Initiated in 2019, the project has produced the following accomplishments. Several generations of PGM-free electrocatalysts were synthesized using sacrificial support method, rationally selected precursors, conditions and treatments (Figure 2).

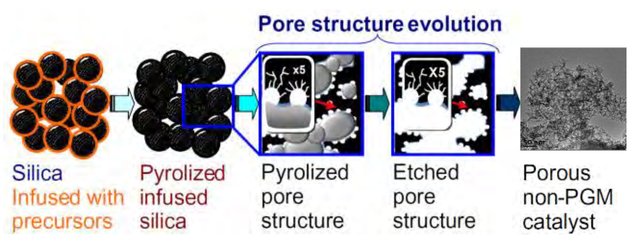

Figure 2. General schematic of used sacrificial support method for Fe-N-C catalyst synthesis.

The chosen catalyst synthesis led to formation of atomically dispersed M-N_x moieties and increase its amount due to creation of additional defects in carbon matrix. The electrocatalysts are characterized by advanced textural properties: high surface area and large pore volume. Raman spectroscopy

[6] Adapted from Asset, T., et al. (2019). Investigating the nature of the active sites for the CO_2 reduction reaction on carbon-based electrocatalysts. ACS Catalysis, 9(9), 7668-7678. https://doi.org/10.1021/acscatal.9b01513

demonstrated that materials maintains substantial level of graphitization.

It should be noted that the PGM-free catalysts loading in MEAs is in the range of 2-4 mg_{cat} cm^{-2}, which forms CCL with thickness up to 100 µm, whereas Pt-containing electrodes have catalyst content of 0.1-0.4 mg_{Pt} cm^{-2} with maximum thickness of 10-12 µm. In addition, PGM-free electrocatalysts are typically characterized by large primary catalyst particles with size higher than 1 µm, which affects their integration into the electrode structure and impacted development of three-phase boundaries and proton conductivity.

In order to modify intrinistic catalyst properties we evoluated impacts of Mn additives on the Fe-N-C morphology and performance. It was found that introduction Mn in combination with varioation of synthesis parameters led to formation of surface area of 1400 m^2 g^{-1} and 300-400 nm primary particles. Integration of the Fe-Mn-N-C catalysts into the electrode structure showed that CCL consisted of grains with size from several to 20 µm, which were bounded together with ionomer and developed porous network penetrating the thick CCL (Figure 3).

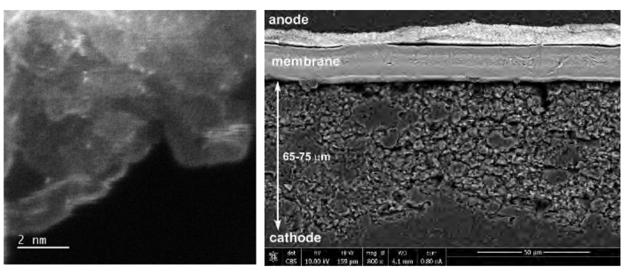

Figure 3. HRTEM and SEM images of Fe-Mn-N-C catalysts and MEA cross section. Atomically dispersed metal (Fe, Mn) centers are presented as bright dots at TEM images.

Using Focus Ion Beam SEM method, it was determined that Fe-Mn-N-C CCL were characterized by the highest porosity (19%) (Figure 4) which together with high hydrophobicity of the electrode improved water management and prevented flooding.

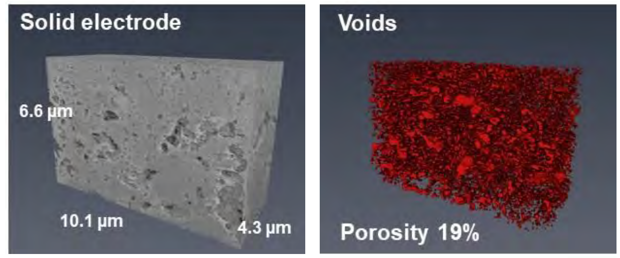

Figure 4. 3D reconstruction of solid electrode (SE) and voids for Fe-Mn-N-C.

Electrochemical evaluation of the membrane electrode assemblies showed that the Fe-Mn-N-C catalysts revealed exceptional proton conductivity and oxygen permeability, which improved overall performance of PGM-free PEMFCs even with highly loaded and thick cathodes (Figure 5).

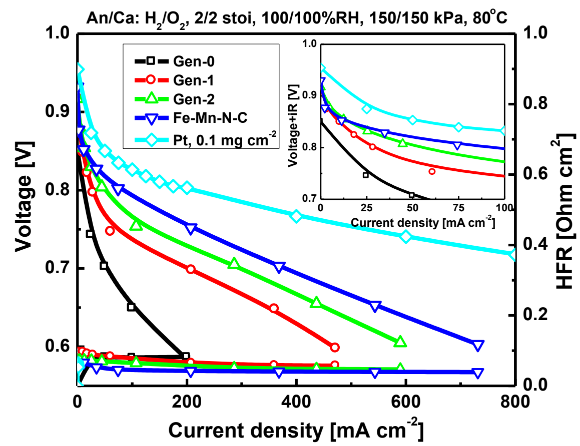

Figure 5. Polarization curves for different generation of PGM-free and Pt-based MEAs. An/Ca: H_2/O_2, 0.5 slpm, 100%RH, 150 kPa, T_{cell}=80°C.

In order to understand the performance we evaluated more than 150 MEAs and studied impacts of membrane types, membrane thickness, ionomer EW and its loading in the cathode electrode (30-60%); PGM-free catalyst content (0.5-6.0 mg cm^{-2}) and electrode structure design. We developed testing protocols and procedures to obtaine full set of electrochemcial diagnistics of the MEAs.

The gained expertise and knowledge allowed us to improve the electrocatalyst and CCL design further and developed 5th generation of the material with performance approaching performance of Pt-containing MEAs at kinetic conditions (Figure 6). However, mass transport and durability of the PGM-free fuel cells still require further improvement and these are tasks for the future projects.

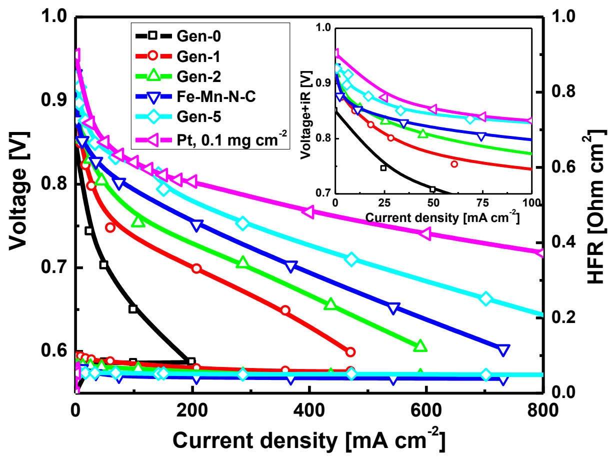

Figure 6. Polarization curves for different generation of PGM-free and Pt-based MEAs. An/Ca: H_2/O_2, 0.5 slpm, 100%RH, 150 kPa, T_{cell}=80°C.

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

- 2022, T. Reshetenko, et al., **Design of PGM-free cathodic catalyst layers for advanced PEM fuel cells**, Applied Catalysis B: Environmental, Vol. 312, Paper 121424.
- 2022, S. Akula, et al., **Mesoporous textured Fe-N-C electrocatalysts as highly efficient cathodes for proton exchange membrane fuel cells**, Journal of Power Sources, Vol. 520, Paper 230819.
- 2020, T. Reshetenko, et al., **Electron and proton conductivity of Fe-N-C cathodes for PEM fuel cells: A model-based electrochemical impedance spectroscopy measurement**, Electrochemistry Communications, Vol. 118, Paper 106795.
- 2020, T. Reshetenko, et al., **The Effect of Proton Conductivity of Fe–N–C–Based Cathode on PEM Fuel cell Performance**, Journal of the Electrochemical Society, Vol. 167, Issue 8, Paper 084501.
- 2020, T. Reshetenko, et al., **Effects of cathode proton conductivity on PGM-free PEM fuel cell performance**, Presented at the ECS 2020-02 Meeting, Honolulu, Hawai‘i, October 4-9, Abstract 2686.
- 2019, T. Reshetenko, et al., **Impedance Spectroscopy Characterization of PEM Fuel Cells with Fe-N-C-Based Cathodes**, Journal of the Electrochemical Society, Vol. 166, Issue 10, pp. F653-660.
- 2019, T. Reshetenko, et al., **Comprehensive Characterization of PGM-Free PEM Fuel Cells Using AC and DC Methods**, Presented at the ECS 2019-02 Meeting, Atlanta, Georgia, October 13-17, Abstract 1617.
- 2019, A. Serov, et al., **PGM-Free Oxygen Reduction Reaction Electrocatalyst: From the Design to Manufacturing**, Presented at the ECS 2019-01 Meeting, Dallas, Texas, May 26-30, Abstract 1487.

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

Contact: Tatyana Reshetenko, tatyanar@hawaii.edu

Last Updated: November 2022

D5: Transition Metal Carbide Catalysts for Electrochemical Applications

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

BACKGROUND: The commercial application of a number of electrochemical technologies would benefit from the availability of low cost, efficient, and durable catalysts. Pt-group-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. VRFBs have recently attracted considerable attention for large-scale energy storage. Carbon-based materials have been investigated as electrodes for VRFBs. However, they often show limited activity and reversibility. 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.

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. The use of a carbon material as the carbon source and support favors the formation of nano-sized carbides that are expected to possess a large specific surface area and be durable due to a stronger catalyst and support interaction. As shown in Figure 1, vanadium carbides with V_8C_7 phase [JCPDS: PDF 89-1096] are obtained. The average V_8C_7 crystallite size calculated by Scherrer's equation based on (222) diffraction peak is 32 nm. To investigate the potential use of vanadium carbides as catalysts for reactions involving V^{5+}/V^{4+} (VO_2^+/VO^{2+}), cyclic voltammetry was performed in N_2-saturated 3 M H_2SO_4 (Figure 2).

There is an obvious oxidation current at potentials higher than 0.8 V (vs. RHE) for vanadium carbides, and the oxidation current decreases in the 2nd and 3rd cycles, which may be due to the oxidation of V_8C_7 crystals. Vanadium carbides (V_8C_7 phase) are not electrochemically stable at potential higher than 0.8 V (vs. RHE).

Synthesis approaches to achieve high surface area and electrochemically stable carbides are being explored.

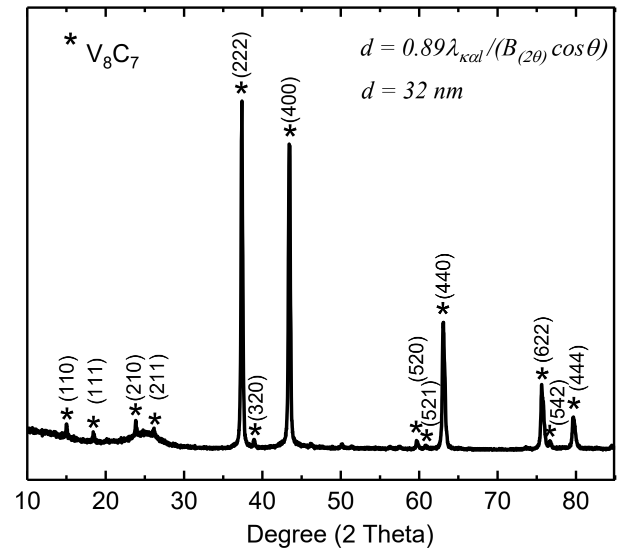

Figure 1. X-ray diffraction patterns of vanadium carbides.

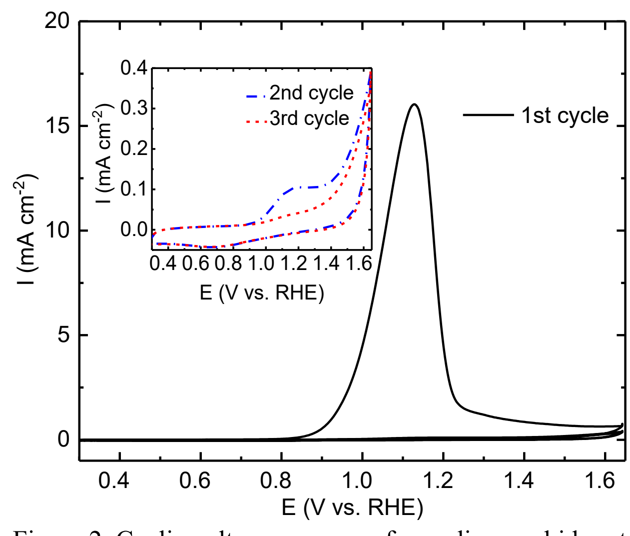

Figure 2. Cyclic voltammograms of vanadium carbides at 5mV s^{-1} in N_2-saturated 3 M H_2SO_4 at 25°C.

Funding Source: Office of Naval Research

Contact: Jing Qi, qijing@hawaii.edu

Last Updated: November 2022

D6: 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. 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 (FC) 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 small FCs (0.5-5 kW) while retaining performance.

BACKGROUND: Hydrogen FCs have the potential to be a disruptive technology for energy storage and power production for the DoD. Their ability to store energy efficiently, produce electric power with low signature, and operate with minimum maintenance provide an important compliment to battery electric systems and internal combustion engines. Hydrogen FCs' 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 FCs, 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 FCs 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 FC 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.

PROJECT STATUS/RESULTS: 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 of FCs 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 FC system architecture and increased heat rejection that leads to volume savings in the FC system that can be applied to hydrogen storage space claim.

This project began in Fall 2022. Initial efforts underway focus on integration of thin mesh metallic current collectors into fuel cell electrodes.

Funding Source: Office of Naval Research

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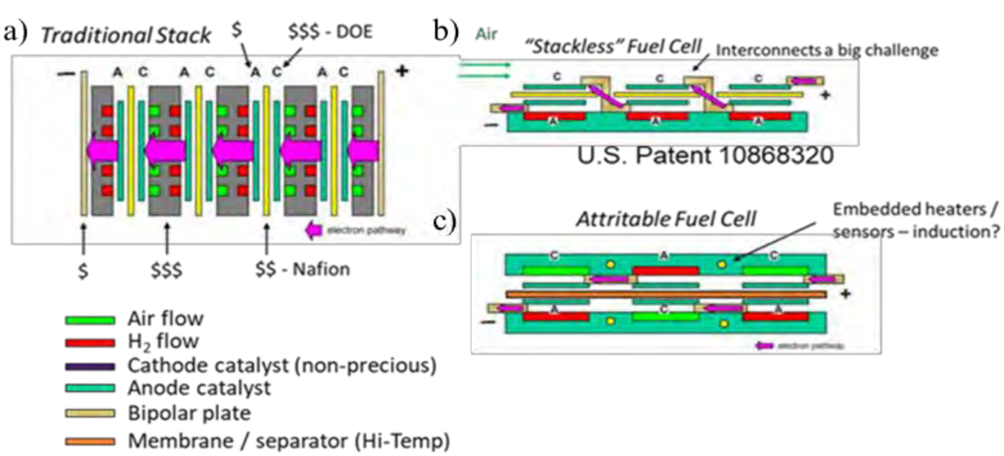
Last Updated: October 2022



D7: Proton Conducting Electrolytes for HT-PEMFC

OBJECTIVE AND SIGNIFICANCE: 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 as the catalyst layer of the high temperature proton exchange membrane fuel cell (HT-PEMFC) to overcome the issue of phosphoric acid (H_3PO_4) leaching. High temperature operation would facilitate the PEMFC system meeting with the U.S. DOE technical targets at performance, power and energy density, cost, and liability by inhibiting the poisoning effects of air pollution and fuel impurities and simplifing the water and heat management of the system.

BACKGROUND: PEMFC is considered a promising clean energy technology for the transportation and stationary applications. The contamiants in air and hydrogen fuel are big challenge for the Pt catalysts in the typical PEMFC when it is operated in the realistic atmosphere. The high temperature operation (150-200°C) of PEMFC 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. The high temperature operation also facilitates the heat transport and the mass transfer of oxygen and hydrogen because the high temperature differential and the absence of liquid water in the cell, respectively. With those advantages, HT-PEMFCs would eliminate the humidifier and simflify 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. But H_3PO_4 leaching is a big issue during operation, especially in the catalyst layer.

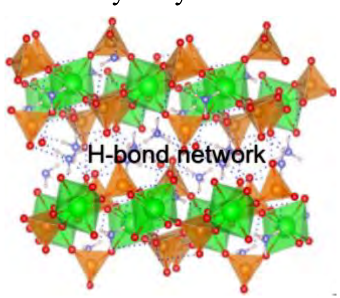


Figure 1. H-bond network in the layered structures of the inorganic proton conducting materials.

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.

PROJECT STATUS/RESULTS: At HNEI, a novel inorganic layered structure material is being developed for HT-PEMFCs as proton conducting electrolyte. The candidate will be integrated into the in the catalyst layers of high-temperature membrane electrode assemblies (HT-MEA) of the contaminant tolerant fuel cells for harsh environments.

The capability to synthesize, treat, and handle the materials has been established. A concept paper was submitted to U.S. DOE for seeking potential funding.

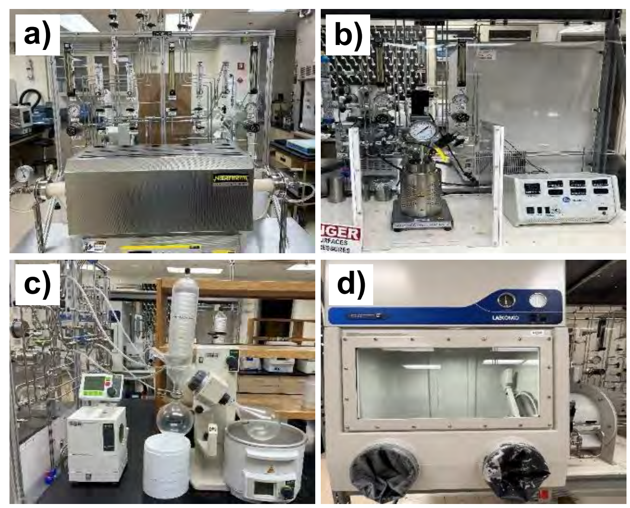


Figure 2. Tub furnace (a), high temperature and high pressure reactor (b), rotating evaporator (c), and glove box (d) for synthesizing, treating, handing, and storing the novel proton conducting material.

The project is ongoing as the multilayer material will be synthesized; the structure, composition, and proton conductivity will be characterized; the material will be integrated into the catalyst layers of HT-MEAs and the performance of HT-PEMFC will be evaluated at 150-200°C.

Funding Source: Office of Naval Research

Contact: Yunfeng Zhai, yunfeng@hawaii.edu

Last Updated: November 2022

D8: Proton Exchange Membrane Fuel Cell Producing Hydrogen Peroxide

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to modify a proton exchange membrane fuel cell (PEMFC) to optimizer hydrogen peroxide synthesis. Hydrogen peroxide is widely useful by many industries, as well as the military, as an environmentally friendly disinfectant. The main method for hydrogen peroxide production today, an anthraquinone-oxidation process, is energy-intensive, expensive, produces waste negatively impacting 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 to develop an alternative, electrochemical method for synthesizing hydrogen peroxide that also produces energy, eliminates waste by producing aqueous solutions of varied hydrogen concentrations, and is scalable to address the 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, because the economics are such that the process can only 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).

$$O_2 + 2H^+ + 2e^- \rightarrow H_2O_2 \quad \text{(Equation1)}$$
$$O_2 + 4H^+ + 4e^- \rightarrow H_2O \quad \text{(Equation 2)}$$

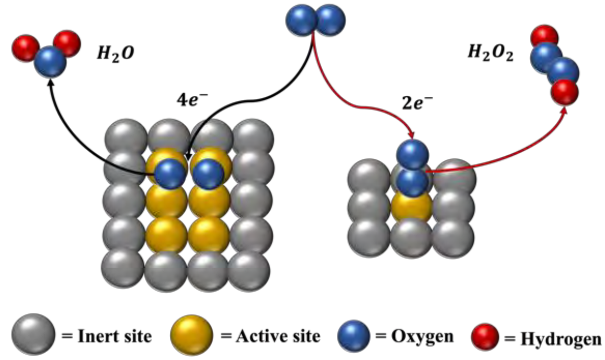


Figure 1. $2e^-$ & $4e^-$ pathways for the ORR.

PROJECT STATUS/RESULTS: HNEI has reviewed the concept, invention disclosure, and relevant literature. As a result of the review and prior results, an experimental plan and detailed procedures for a selective catalyst for the $2e^-$ pathway has been developed and will be tested in further experimentation. This innovative approach to the synthesis of hydrogen peroxide will enable onsite production of this chemical, and power.

Experiments will begin by verifying the co-generation of hydrogen peroxide and power ex-situ in a Rotating Ring Disk Electrode (RRDE). Experiments will then be performed in-situ in a PEMFC for further verification and identification of modifications to design of fuel cell to increase removal rate of hydrogen peroxide and limit decomposition to maximize performance, productivity, and yield. HNEI will also begin verification experiments ex-situ in the RRDE. PEMFC assembly, modification, and operation training will ensue thereafter.

The project is ongoing and will continue through at least Fall 2023.

Funding Source: Office of Naval Research

Contact: Alexandra Fernandez, af41@hawaii.edu

Last Updated: November 2022

D9: Battery Energy Storage Systems Durability and Reliability

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

BACKGROUND: Battery Energy Storage Systems (BESS) show promise in mitigating many of the effects of high penetration of variable renewable generation. HNEI has initiated an integrated research, testing, and evaluation program to assess the benefits and durability of grid-scale BESS for various ancillary service applications. Throughout the course of this project, three BESS serving different grid applications were deployed on different islands. The first one was deployed in December 2012 on the Big Island of Hawaiʻi. The other two were deployed on Molokaʻi and Oʻahu in 2016. Usage was closely monitored and maintenance cycles using protocols recommended by the manufacturer, as well as custom HNEI protocols, were applied.

PROJECT STATUS/RESULTS: Usage from the BESS was carefully analyzed to facilitate laboratory testing of individual cells representative of actual operating conditions. All cells used in the demonstrations and laboratory testing were Lithium titanate cells from Altairnano. Around 100 cells were tested in the lab to monitor aging patterns, reproduce the aging observed in real life, and accelerate the degradation.

This project showed that, because of their lower intrinsic voltages, these cells are far less sensitive to degradation induced by calendar aging and high state of charges than traditional Li-ion batteries. Moreover, their capacity fading pace is also slower.

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

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

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

Funding Source: Office of Naval Research

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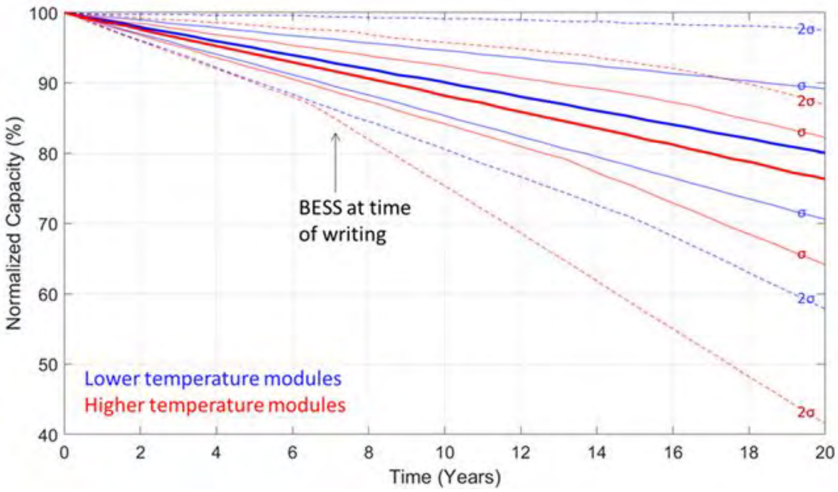
Last Updated: November 2022



ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

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

PRESENTATIONS:

1. 2022, M. Dubarry, et al., **Lithium Titanate Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the Material Research Society Spring Meeting, May 8-13.
2. 2021, M. Dubarry, et al., **Battery Durability and Reliability under Electric Utility Grid Operations**, Presented at the International Battery Seminar & Exhibit, March 9-11.
3. 2021, M. Dubarry, **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the Alaska Energy Storage Workshop, January 12-13.
4. 2020, G. Baure, et al., **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the ECS PRiME Meeting, October 4-9.
5. 2020, M. Dubarry, et al., **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the International Coalition for Energy Storage and Innovation Conference, Sydney, Australia, March 1-4.
6. 2019, M. Dubarry, et al., **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the International Battery Association Meeting, March 3-8.
7. 2018, A. Devie, et al., **Battery Durability and Reliability Under Electric Utility Grid Operations**, Presented at the ECS AiMES Meeting, Cancun, Mexico September 30 - October 4.
8. 2017, M. Dubarry, et al., **Asia Pacific Research Initiative for Sustainable Energy Systems: Batteries for Grid Management**, Presented at ONR Program Review, Washington, DC, March 28-30.
9. 2016, M. Dubarry, **Overcharge Study in $Li_4Ti_5O_{12}$ Based Lithium-Ion Pouch Cell**, Presented at the International Battery Association Meeting, Nantes, France, March 20-25.

D10: 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 inform 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.

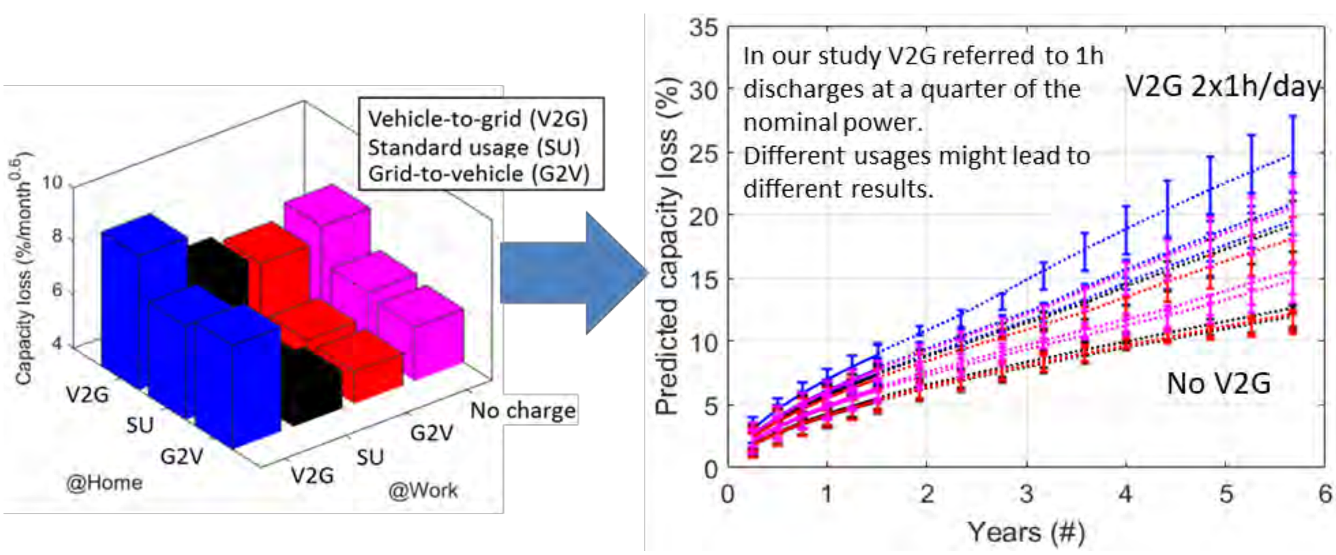
Current work with DSTG (Australia) involves an experimental campaign of more than 700 cells tested under a HNEI defined design of experiments to predict the degradation of MW systems and maximize durability and reliability in the field. Collaborative work is also ongoing with SANDIA National Laboratory and Aalborg University (Denmark).

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

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

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2022



Additional Project Related Links

Papers and Proceedings:

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

Presentations:

1. 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.
2. 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.
3. 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, Hawai‘i, January 5-10.
4. 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.
5. 2016, M. Dubarry, et al., **Path Dependence in Lithium-Ion Batteries Degradation**, Presented at the ECS PRiME Meeting, Honolulu, Hawai‘i, October 2-7.
6. 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.
7. 2015, A. Devie, et al., **Investigation of Consistency of Aging Mechanism inside a Batch of Commercial 18650 Lithium-ion Cells**, Presented at the 225th ECS Meeting, Orlando, Florida, May 11-15.
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.

D11: Battery Intelligence: Diagnosis and Prognosis

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to develop approaches, tools, and protocols to improve batteries diagnosis and prognosis via non-invasive in-operando techniques.

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

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

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

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

Machine learning and artificial intelligence are also starting to play a crucial role to diagnose and prognose batteries. However, their accuracy is limited by the little to no training data available to validate algorithms. To solve this issue, HNEI applied the mechanistic modeling approach to develop the first synthetic training datasets using computer-generated voltage curves. Recent work simulated battery usage of batteries associated with solar panels.

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

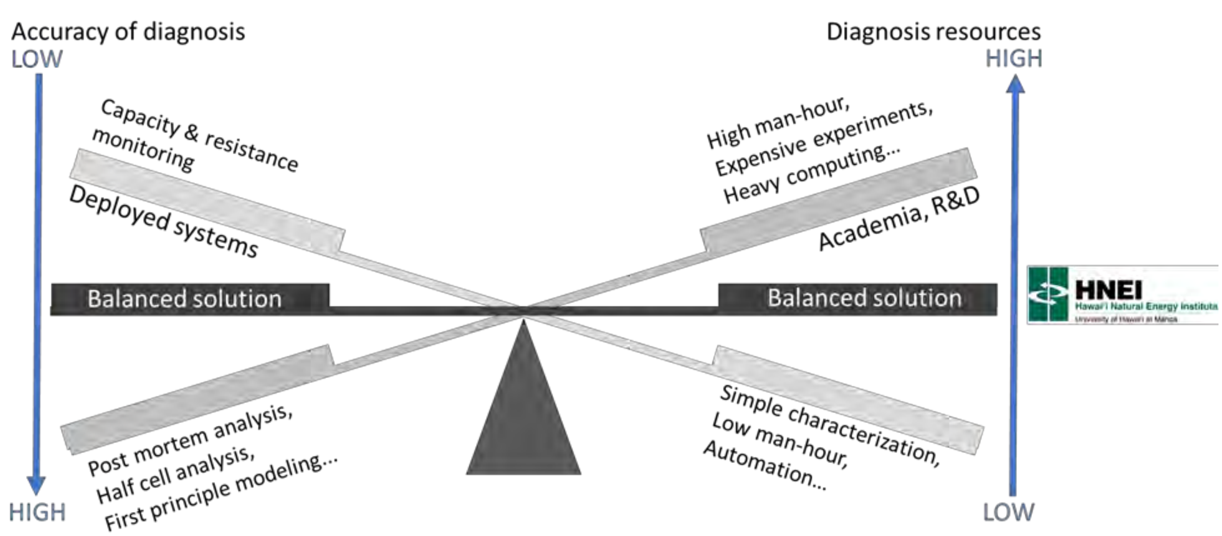
PROJECT STATUS/RESULTS: This project is currently ongoing with three industrial collaborations on different aspects of the problem. A full suite of software and models were developed. The main model has been licensed by more than 90 organizations worldwide.

This work led to 39 publications, including the ones listed on the following page and one patent.

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

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2022



Additional Project Related Links

Papers and Proceedings:

Battery Testing

1. 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**)
2. 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**)
3. 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**)
4. 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.
5. 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.
6. 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**)
7. 2019, A. Barai, et al., **A comparison of methodologies for the non-invasive characterisation of commercial Li-ion cells**, Progress in Energy and Combustion Science, Vol. 72, pp. 1-32. (Open Access: **PDF**)
8. 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.
9. 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**)
10. 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**)
11. 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.
12. 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. 2022, M. Dubarry, et al., **Perspective on Mechanistic Modeling of Li-Ion Batteries**, Accounts of Material Research, Vol. 3, Issue 8, pp. 843-853.
2. 2019, S. Schindler, et al., **Kinetics accommodation in Li-ion mechanistic modeling**, Journal of Power Sources, Vol. 440, Paper 227117.
3. 2019, M. Dubarry, et al., **Battery energy storage system modeling: Investigation of intrinsic cell-to-cell variations**, Journal of Energy Storage, Vol. 23, pp. 19-28. (Open Access: **PDF**)
4. 2019, M. Dubarry, et al., **Battery energy storage system modeling: A combined comprehensive approach**, Journal of Energy Storage, Vol. 21, pp. 172-185. (Open Access: **PDF**)
5. 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.
6. 2016, M. Dubarry, et al., **Cell-balancing currents in parallel strings of a battery system**, Journal of Power Sources, Vol. 321, pp. 36-46.
7. 2016, M. Berecibar, et al., **Degradation Mechanism Detection for NMC Batteries based on Incremental Capacity Curves**, World Electric Vehicle Journal, Vol. 8, Issue 2, pp. 350-361. (Open Access: **PDF**)
8. 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.

9. 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.
10. 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.
11. 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**)

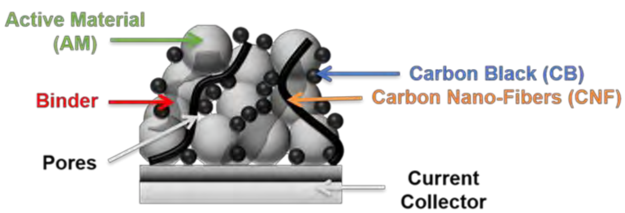
PRESENTATIONS:

1. 2022, M. Dubarry, et al., **Mechanistic Li-Ion Battery Modeling, What's Next?**, Presented at the 242th ECS Meeting, Atlanta, GA, October 9-13.
2. 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.
3. 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.
4. 2021, M. Dubarry, et al., **Big Data for Li-Ion Battery Diagnosis and Prognosis**, Presented at the Advanced Automotive Battery Conference, San Diego, California, December 7-9.
5. 2021, M. Dubarry, et al., **A New Insight into Blended Electrodes**, Presented at the 240th ECS Meeting, Orlando, Florida, October 10-14.
6. 2021, M. Dubarry, et al., **Big Data for Li-Ion Diagnosis and Prognosis**, Presented at the 239th ECS Meeting, May 30 - June 3.
7. 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.
8. 2017, M. Dubarry, **Non-intrusive operando battery diagnosis and prognosis**, Presented at the Pacific Rim Conference on Ceramic and Glass Technology Meeting, Waikoloa, Hawaiʻi, May 21-26.
9. 2016, D. Anseán, et al., **Lithium Plating Quantification in Commercial Graphite‖$LiFePO_4$ Batteries**, Presented at the ECS PRiME Meeting, Honolulu, Hawaiʻi, October 2-7.
10. 2015, A. Devie, et al., **Intrinsic degradation variability in commercial lithium-ion batteries**, Presented at the 228th ECS Meeting, Phoenix, Arizona, October 11-16.
11. 2015, M. Dubarry, et al., **State-of-Charge determination in imbalanced lithium-ion battery packs**, Presented at the 228th ECS Meeting, Phoenix, Arizona, October 11-16.
12. 2015, M. Dubarry, et al., **Two-point State of Charge Determination In Lithium-Ion Battery Packs**, Presented at the 227th ECS Meeting, Chicago, Illinois, May 24-28.
13. 2015, M. Dubarry, et al., **Two-point State of Charge Determination In Lithium-Ion Battery Packs**, Presented at the International Battery Association Meeting, Waikoloa, Hawaiʻi, January 5-9.

D12: Battery Electrode Optimization

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to optimize battery electrodes to improve performance by understanding local degradation mechanisms and by tuning the electrode architecture.

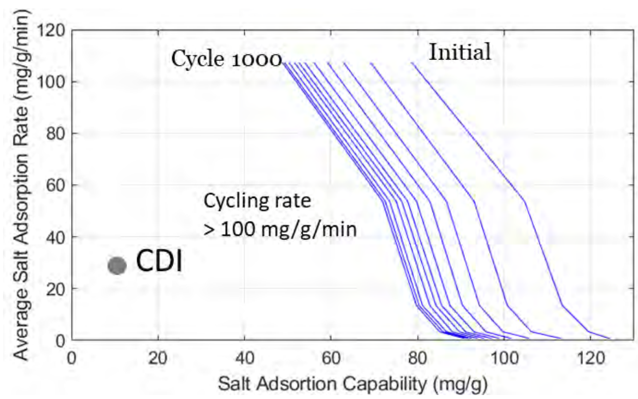
BACKGROUND: Advanced energy conversion devices typically rely on composites electrodes made of several materials interacting with one another. Understanding their individual and combined impact on degradation is essential in the pursuit of the best possible performance and safety. In this project, we 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.



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

In this project, the DoE approach is applied to two types of electrodes: high power electrodes for lithium batteries (ONR funded, in collaboration with the University of Montreal) and sodium intercalation electrodes (DOI 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 1,000 times with improved performance compared to traditional materials (CDI).



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

Research conducted for this project is completed in the **PakaLi Battery Laboratory**. This program led to the three publications, a number of presentations, and a review listed on the following page so far.

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

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

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2022

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. 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.
3. 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. 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.*
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. 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.
4. 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.
5. 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.

D13: Vanadium Flow Battery with High Concentration Electrolytes

OBJECTIVE AND SIGNIFICANCE: The objective of this research activity is to develop a high power and energy density, durable and safe vanadium flow battery (VFB) with novel catalysts and high concentration of vanadium electrolytes. The proposed research has the potential to double the energy density of vanadium electrolytes, and significantly improve the negative electrode performance. This work would facilitate the VFB system achieving the durability and cost required for large-scale energy storage applications.

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

To date, VFB is technically the most advanced system of the under-developing flow batteries. Due to it using only one element (vanadium) in both tanks, it overcomes cross-contamination degradation, a significant issue with other flow batteries that use more than one active element. The vanadium ions with oxidation states of 2+/3+ and 4+/5+ are used as active species in the negative and positive electrolytes respectively. The power density of VFBs depends on the redox reactions activities and the concentration of vanadium ions in the electrodes (graphite felts). The energy density is determined by the concentration of vanadium ions: the higher concentration, the higher energy density. The maximum concentration of electrolytes are limited by the solubility of $VOSO_4$, a starting electrolyte, and the stability of vanadium species. The solubility of V^{2+}, V^{3+}, and VO^{2+}(4+) decreases with increase of the sulfate concentration due to the common-ion effect, but the stability and solubility of VO_2^{+}(5+) increase with increase of the acid concentration. Therefore, the concentration of sulfuric acid and vanadium is usually controlled at 2-4 M and 1-2 M, respectively which is relatively low for the energy storage application. In addition, VFBs usually require expensive polymer membranes due to the highly acidic and oxidative environment which lead to high system costs. The low energy densities, along with high capital cost, make it difficult for the current VFBs to meet the performance and economic requirements for broad market penetration. To reduce VFBs' cost, a number of research has been conducted which aims to improve the vanadium electrolyte energy density and the system performance by increasing vanadium concentration.

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

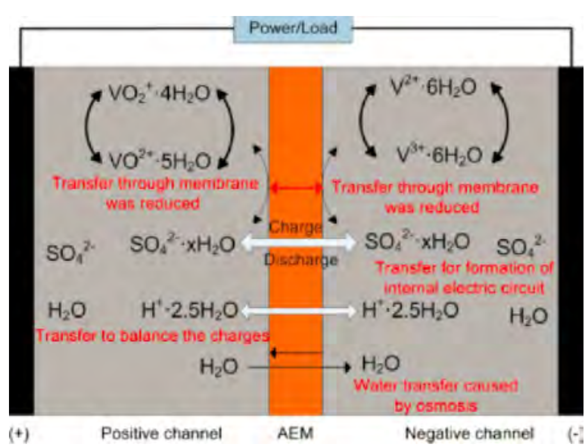


Figure 1. The features of a VFB cell with AEMs.

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

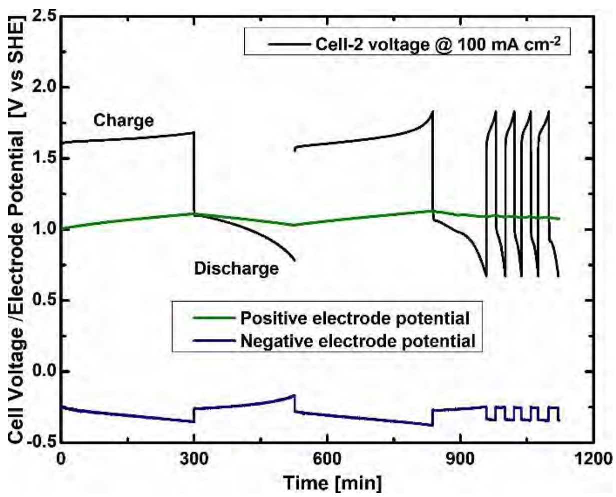


Figure 2. Charge-discharge cycles of VFB with an AEM and 3 M electrolytes in both sides.

An electrochemical procedure has been developed to prepare a low acid (H^+ low to 0.1 M) and high vanadium concentration (V up to 5 M) negative electrolytes. The acid concentration decreases by a factor of more than 30 and the vanadium concentration doubled compared to the state of the art. Single cells operated with the high concentration vanadium electrolytes were evaluated with different AEMs and demonstrated good performance and low overpotentials for both positive and negative electrodes.

Challenges were identified as the low chemical and mechanical stability and the high proton permeability of the AEMs, and the low ionic conductivity of the AEMs and the negative electrolytes.

This project is now completed.

Funding Source: Office of Naval Research

Contact: Yunfeng Zhai, yunfeng@hawaii.edu

Last Updated: November 2022

E1: Printable Photovoltaics

OBJECTIVE AND SIGNIFICANCE: The objective of this program is to develop high-throughput ink-based fabrication techniques for light-weight thin-film photovoltaics (PV). This approach has the potential to 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 the HNEI 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.

This project is currently focused on a multi-compound alloy ($CuInSe_2$, CISe), a material which meets the mechanical and weight requirements for light weight flexible PV. 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% (Septina, 2021). 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.

- 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 Mater. Chem. A, Vol. 9, Issue 16, pp. 10419-10426.

Funding Source: Office of Naval Research

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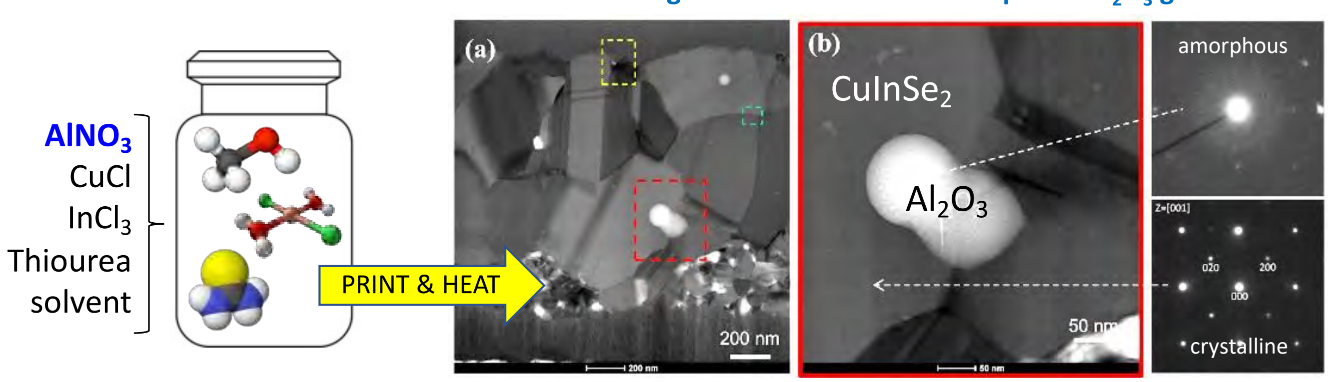
Molecular ink

Cross-section of a 11% efficient CISe printed solar cell containing isolated nano-sized amorphous Al_2O_3 grains



E2: 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 Screening of N-heterocycle-magnesium borohydride (LOHC-$Mg(BH_4)_2$) solutions with and without catalyst for optimal (de)hydrogenation behavior is under investigation. Due to the high volumetric, releasable H_2 capacity that has been found for 1:2 $Mg(BH_4)_2$/pyrrolidine solution, we are screening various concentrations from 1:2 to 1:8 solutions of $Mg(BH_4)_2$ and other N-heterocycles.

The studies allow the identification of the optimal N-hetrocycle based LOHC-$Mg(BH_4)_2$ solutions for development as hydrogen carriers. The N-heterocycles analyzed include (de)hydrogenated methyl imidazole, butyl-imidazole, N-methylindole, morpholine, 1,2 dimethy-imidazole, and quinolone. The screening reactions of the LOHC-$Mg(BH_4)_2$ solutions without catalysts were performed in Parr mini-reactors at 180-200° C for 24 hours. Hydrogen evolution from the solutions was confirmed by the increase in pressure of the reactor vessels. Analyses of the dehydrogenated materials is being performed utilizing ^{1}H and ^{11}B nuclear magnetic resonance spectroscopy (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, will be subsequently treated to 100-180° C, with and without catalyst, to determine the extent of reversible H_2 uptake of the system, enabling determination of best solutions for development as hydrogen carriers.

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

Contact: Godwin Severa, severa@hawaii.edu

Last Updated: November 2022

E3: Development of Advanced Magnesium Boride Hydrogen Storage Materials

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to obtain key information needed for the development of a comprehensive, multi-scale computational model of reversible hydrogenation of magnesium boride (MgB_2) to magnesium borohydride ($Mg(BH_4)_2$). If successful, the project will significantly accelerate the discovery of boride materials for practical hydrogen storage applications. The project provides excellent training on state-of-the-art instrumentation to the participating UH graduate students and early career scientists, and enhances research competitiveness at UH by strengthening ties with U.S. national laboratories.

BACKGROUND: The magnesium boride/magnesium borohydride (MgB_2/$Mg(BH_4)_2$) material system is one of the few cyclable materials that has a demonstrated gravimetric hydrogen storage capacity greater than 11 wt% and hence has a potential to be utilized in a hydrogen storage system that meets U.S. DOE hydrogen storage targets. This project works towards obtaining experimental information of: 1) the bulk, nano-scale, and meso-scale structural changes occurring at elevated pressure following mechano-chemical modification of MgB_2; 2) the reaction pathway of the reversible hydrogenation of MgB_2 to $Mg(BH_4)_2$; 3) the effect of elevated pressure and mechano-chemical modification on the chemical reaction pathways; 4) the interactions at solid-gas interfaces and particle surfaces; and 5) the kinetics and thermodynamic parameters associated with each step of the hydrogenation reaction pathway. The fundamental experimental information derived from the project will be used for the development of a comprehensive, multi-scale computational model of reversible hydrogenation of MgB_2 to $Mg(BH_4)_2$ at the Lawrence Livermore National Laboratory.

This EPSCoR project is a collaborative effort between UH (HNEI, Mechanical Engineering (ME), Department of Chemistry, and Hawai‘i Institute of Geophysics) and the National Renewable Energy Laboratory. HNEI's role is currently focused on syntheses of nano-sized MgB_2 thin films, followed by calorimetry studies of the initial stages of H_2 uptake of the modified MgB_2.

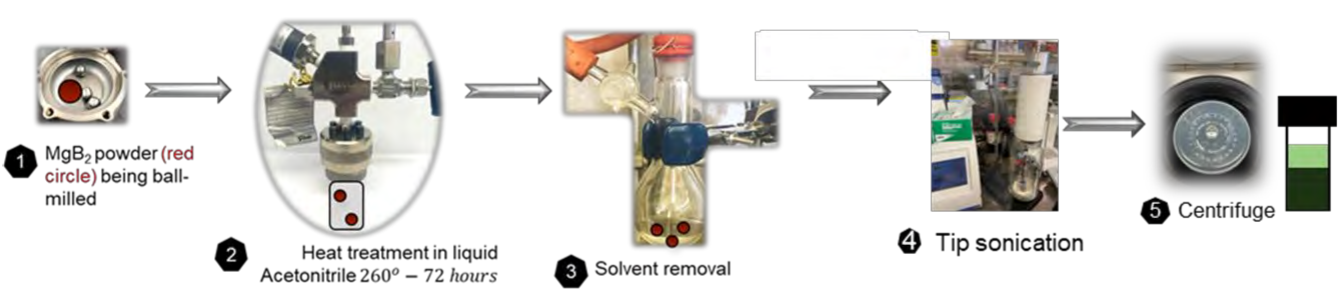
PROJECT STATUS/RESULTS: The effort on syntheses of nanosized thin films of magnesium boride using a combination of mechanochemistry, heat treatment, and sonication was performed. The samples containing the magnesium boride nano structures were prepared through a five step process involving 1) mechanical milling, 2) thermal treatment at 180°C, 3) Schlenk line solvent removal, 4) ultra-sonication and 5) centrifugation as seen in the figure below. The MgB_2 nano-sheets were deposited as thin films on gold (Au) surface for further testing and characterization in collaboration with Prof. Brown at the ME department. XPS analyses confirmed the presence of MgB_2 in the deposited film. Scanning transmission electron microscopy (STEM) indicated a MgB_2 film thickness of about 3.9 nm. The successfully synthesized and deposited thin films will be used to study the energetics of first steps of hydrogen adsorption on MgB_2 using a Quartz Crystal Microbalance (QCM) in collaboration with Prof. Brown.

Future work will involve complimentary calorimetry studies of the initial stages of hydrogen uptake of synthesized MgB_2 thin films using the high pressure differential scanning calorimeter in our laboratory.

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

Contact: Godwin Severa, severa@hawaii.edu

Last Updated: November 2022



E4: 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, easily regenerable, 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 a 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.

Our research is focused on fabricating an 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.

PROJECT STATUS/RESULTS: During this period, we initially continued the testing and benchmarking of the performance of the FO system using commercial draw solutes. Analyses of the FO system data showed high dispersion in water flux values and large deviation from literature values, necessitating an optimization of the FO system. Hence, we began to optimize the fabrication of the FO system (Figure 1) to enable more accurate determination of water flux and improve the consistence of the water flux measurements from the FO system.

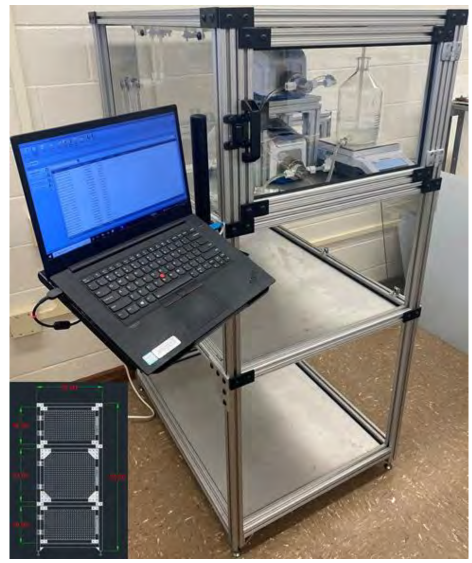


Figure 1. HNEI fabrication and optimization of a forward osmosis water flux testing system.

Our analyses of data from current benchmarking tests using commercial draw solutes and deionized water feed solution, indicates consistency of water flux values with literature. State of art concentrated draw solutions are currently being prepared and tested for their potential to absorb high salinity sea water using the FO system. One peer reviewed manuscript was published on synthesis and characterization of novel metallo ionic liquid materials. These new ionic salts are also currently being evaluated for their potential use as FO high water flux draw solutes.

Funding Source: Office of Naval Research

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Last Updated: November 2022

E5: UH & UW Materials Research and Education Consortium (MRE-C)

OBJECTIVE AND SIGNIFICANCE: The objective of the University of Hawai‘i (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 bringing 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 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) on Defects in Nanostructures and Layered Quantum Materials: 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) Role of hydrogen in the chemistry of proton-irradiated solids; 4) Strain control of electronic and magnetic properties of solid materials. The results of this research would lead to new materials and understanding of new phenomena critical for solving emerging needs in energy storage and durable space technologies.

The project creates a pathway to recruit, retain, and ensure degree attainment by over 10 student STEM participants, mostly from the targeted URGs. 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; joint seminars; and an annual student symposium.

PROJECT STATUS/RESULTS: The major focus of the past period has been the recruitment and training of PREM undergraduate students into the four research thrusts. The M.O.R.E. strategy encompassing mentoring (M), outreach (O), materials research (R), and materials science education (E) was at the core of implementing MRE-C's objective, including development of a MRE-C website.

The MRE-C research thrusts capitalized on the synergistic expertise of its five UH and seven UW research faculty, and the two institutions' complementary syntheses and characterization resources to create close interdisciplinary collaborations across 7 disciplines which involved training of seven undergraduate students, three graduate students, and three postdocs, inclusive of 4 student exchanges.

Figure 1. UH-UW faculty at a UW-MRSEC Annual All-Hands Workshop, discussing ways to further enhance UH-UW research and education collaborations.

The activities in the four research thrusts were centered on training the student participants, on review of thrust research literature on syntheses and characterization methods, designing and setting up of experiments, performing experiments involving the introducing of defects or dopants into boron compounds, chalcopyrites and mineral oxides, and characterization of materials using XRD and TEM.

Through these efforts the *dopant control in boron compounds for tailored gas sorption* thrust led to the syntheses of nanosized metal borides using mechanochemical and ultra-sonication approaches resulting in discovery of solvents and dopants/additives for metal diborides nanosizing. The current work indicates effective perturbation of bulk TiB_2 structure using alcohol based solvents containing minute amounts of polyethylene glycol.

The *defect modeling, characterization, in ordered vacancy compound chalcopyrites* thrust is in process of developing a manuscript co-authored by UH and UW, on the effect of Al_2O_3 on the photovoltaic performances of chalcopyrite solar materials. This UH-UW collaboration on uncovering the role of Al_2O_3 treatment on defect passivation of chalcopyrites using spectroscopic techniques, is showing PL energy intensity and distribution spectra with a sharp peak at 1.7 eV at low and higher temperatures (4.5K to room temperature) unusual for chalcopyrites with an absorber's bandgap of 1.0 eV.

The thrust on *determination of role of hydrogen in* the chemistry of proton-irradiated solids has effectively prepared proton irradiated mineral oxide samples showing blistering on their surfaces, for further studies using TEM spectroscopy. The oxide samples were polished using focused ion beam (FIB), followed by the irradiation of the samples with D_2^+.

The fourth thrust on *strain control of electronic and magnetic properties of solid materials* synthesized a metal organic ionic salt with potential for spin crossover, $Fe_4(OAc)_{10}[EMIM]_2$ and confirmed the crystal structure using XRD. DFT simulations of the spin crossover behavior of the $Fe_4(OAc)_{10}[EMIM]_2$, suggest spin crossover behavior of the Fe^{2+} at ~49 GPa.

Funding Source: National Science Foundation

Contact: Godwin Severa, severa@hawaii.edu

Last Updated: November 2022

F1: 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. Field measurements and computer simulation were used to assess CO_2 concentrations in several room and HVAC typologies.

BACKGROUND: In past research activities under this subaward (2019-2021), the Hawaiʻi Natural Energy Institute and its collaborators, MKThink and RoundhouseOne, explored the optimization of space utilization to maximize energy efficiency while maintaining comfortable indoor conditions.

In 2022, MKThink was tasked with using computational fluid dynamics (CFD) modeling to evaluate whether methods could be developed to inform instructors about how to maintain high quality indoor air quality in real time. A key project objective of the 2022 phase was to identify and validate methodologies to improve indoor air quality (IAQ) and air circulation in a variety of building typologies. While the Computer Vision technologies were validated in previously reported-upon work at the Bishop Museum, the focus of this phase of the 2022 work plan was to monitor and model indoor air quality at Kapolei Middle School in Kapolei, Hawaiʻi.

PROJECT STATUS/RESULTS: MKThink developed 6 classroom test cases to be field tested and simulated, varying in classroom type, mechanical ventilation, and cooling system types. Thirty-two sensors were installed in the six classrooms, measuring CO_2, temperature, humidity, VOC, as well as door, window, and HVAC operating states. Outdoor ambient CO_2, temperature, humidity, wind speed, and direction data were also collected.

CO_2 levels were evaluated by room type (in-building with exposed perimeter, and portable) and HVAC type (unit ventilator, packaged AC, multi-zone central AC), on an average hourly and daily basis and over the study period. A database platform created by MKThink, known as "4daptive", housed all of the data collected between January and May 2022. Figure 1 are samples of visual analytic tools available in 4daptive to begin to identify issues for which to dive more deeply into.

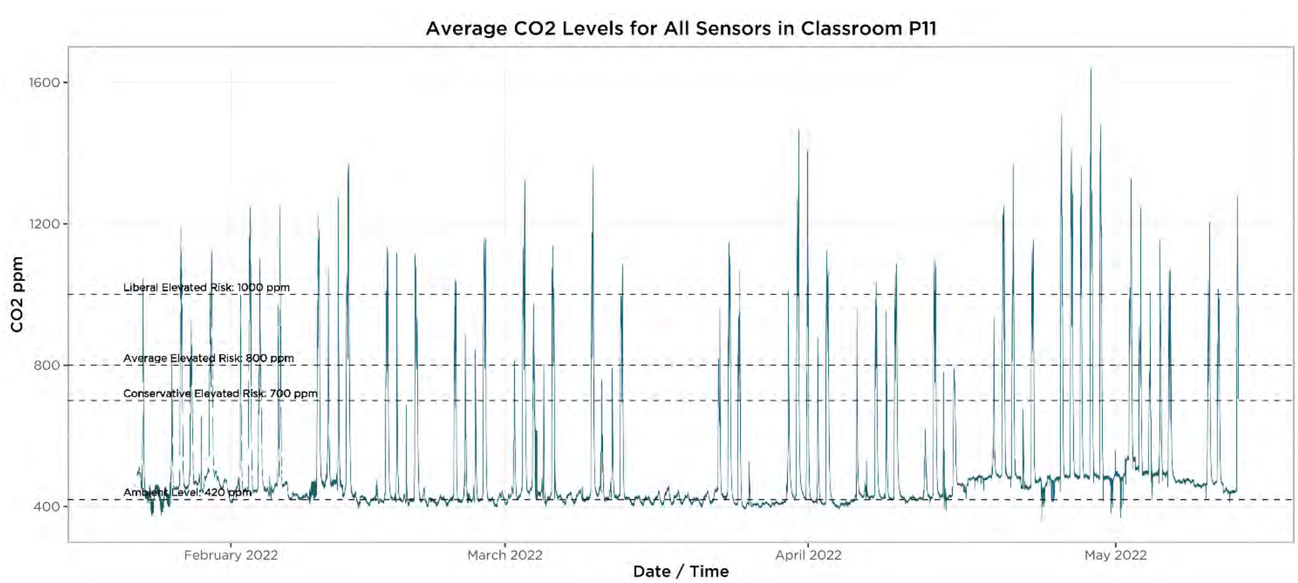
Field data has been collected and is being stored and evaluated using the 4daptive database. At the present, the CFD modeling is being refined and finalized for comparison with field data.

The project is expected to be completed by early 2023.

Funding Source: Office of Naval Research

Contact: Jim Maskrey, maskrey2@hawaii.edu

Last Updated: October 2022



F2: Reducing Greenhouse Gas Emissions from Building Operation

OBJECTIVE AND SIGNIFICANCE: The goal of the project was to provide professional and academic technical support and content development to the City and County of Honolulu Climate Change Commission (CCC), for development of a Commission white paper intended to provided technical and policy guidance to the building industry and city leaders in the context of climate change mitigation. This work was a collaboration between HNEI, the University of Hawaiʻi School of Architecture Environmental Research and Design Lab (ERDL) and the CCC.

BACKGROUND: The CCC is charged with gathering the latest science and information on climate change impacts to Hawaiʻi and to advise the Mayor and City Council as they look to draft policy and engage in planning for future climate scenarios and reducing Honolulu's contribution to global greenhouse gas (GHG) emissions. The city's initiatives are intended to support the efforts of the State of Hawaiʻi in meeting its Climate Action Plan goals.

PROJECT STATUS/RESULTS: The white paper, "***Reducing Greenhouse Gas Emissions From Building Operation – Guidance Document***", was presented to and accepted by the CCC in July 2022.

"This guidance document provides potential actions for the City's consideration in order to mitigate climate change through reduction of GHG emissions from buildings' operational energy use and to adapt to climate change through the implementation of sustainable and resilient development policies and design strategies. This paper supports implementation of the Honolulu Climate Action Plan and Hawaiʻi Clean Energy Initiative and informs the upcoming Honolulu Climate Adaptation Plan.

The body of the paper discusses key factors that shape the built environment, including objectives, context, and potential actionable steps. These key design influences include codes, policies, incentives, and education. The paper then addresses the need for future research in climate change and summarizes a discussion with an industry focus group. The appendix includes specific design strategies for passive and energy-efficient building design."

Based on current trends and studies of Honolulu and other U.S. cities, the Commission suggests the following for the City & County of Honolulu in the paper:

1. Adopt the following targets modified from the 2030 Challenge1 to mitigate the building sector's contribution to climate change.
    a. All new buildings, developments, and major renovations shall be designed to meet a fossil fuel, GHG-emitting, energy consumption performance standard of 70% below the regional average/median for that building type in the 2003 Commercial Building Energy Consumption Survey (CBECS).
    b. At a minimum, an equal amount of existing building area shall be renovated annually to meet a fossil fuel, GHG-emitting, energy consumption performance standard of 70% of the regional average/median for that building type.
    c. The fossil fuel reduction standard for all new buildings and major renovations shall be increased as follows.
        i. 80% in 2025
        ii. 90% in 2030
        iii. Carbon neutral in 2040 (using no fossil fuel GHG emitting energy to operate)
2. Convene a task force to advise the City on creating a roadmap that identifies actions and timelines to meet GHG emissions reduction targets in the Honolulu Climate Action Plan (strategy 5), the Hawaiʻi Clean Energy Initiative, and the 2030 Challenge. This roadmap could include the following recommendations.
3. Support the adoption of the most recent building energy codes and stretch/reach codes to require and motivate best practices.
4. Require building energy benchmarking and disclosure for buildings over 25,000 sf.
5. Encourage existing buildings to improve energy efficiency over time.
    a. Investigate energy auditing, building commissioning, and cost-effective energy-efficient retrofits.
    b. Investigate building performance standards.

6. Incentivize building owners, occupants, designers, and builders to adopt practices to reduce GHG emissions from building operation through financial incentives, energy efficiency standards, tax benefits, loans, grants, expedited permitting, and new financial tools.
7. Support education and ongoing training of professional designers, builders, and code enforcement officials to meet the goals of the 2030 Challenge, the AIA's Framework for Design Excellence, and the previously mentioned codes, policies, practices, and incentives.[7]

Funding Source: Energy Systems Development Special Fund

Contact: Jim Maskrey, maskrey2@hawaii.edu

Last Updated: November 2022

[7] ibid

F3: NELHA & MTA Hydrogen Stations and Fuel Cell Electric Buses

OBJECTIVE AND SIGNIFICANCE: In 2022, HNEI commissioned a 65kg/day hydrogen production and dispensing station on the Island of Hawai‘i at the Natural Energy Laboratory Hawai‘i Authority (NELHA) (Figure 1) and demonstrated on-site fueling of a 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 Hawai‘i Mass Transit Agency (MTA). The knowledge gained in this project will inform the MTA on benefits and issues associated with transitioning from a diesel bus fleet to a zero emissions FCEB fleet in support of the County of Hawai‘i's clean transportation goals. The knowledge will also help inform decisions on other islands.

Figure 1. HNEI's NELHA Hydrogen Station.

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

In additon to the technical and cost analysis, HNEI is developing implementation plans to support the introduction of zero emission transportation systems. HNEI is coordinating with the University of Hawai‘i's Hawai‘i Community College and the County of Hawai‘i 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. Hydrogen Transport Concept.

PROJECT STATUS/RESULTS:

Hydrogen Station: The site infrastructure, as well as the hydrogen production and compression systems equipment, have been installed at NELHA (Figure 3). In 2021, the station was fully commissioned by HNEI and Powertech, the equipment supplier. The first fill of a hydrogen bus for public transportation took place on March 24th, 2022.

Figure 3. HNEI Hydrogen Station.

The station uses a Proton Onsite (now Nel) electrolyzer to produce 65 kg of hydrogen per day at an outlet pressure of 30 bar (440) psi. A HydroPak compressor (Figure 4) compresses the hydrogen to 450 bar (6,600 psi).

Figure 4. HydroPac Compressor.

The system is powered by the Hawaiʻi Electric Light Company (HELCO) grid which includes a substantial fraction of renewable energy including solar, wind, and geothermal.

Hydrogen Transport Trailers: Three trailers (Figure 5) are available for transport between the production and fueling site are certified by the Federal Transit Administration for use on U.S. public roads. The hydrogen cylinders must be recertified every five years.

Figure 5. Hydrogen Transport Trailers.

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

Figure 6. Hydrogen Dispenser.

The fueling dispensers located at NELHA and at MTA are identical except for the addition of a boost compressor at the MTA site integrated into the MTA fueling post (Figure 7). The boost compressor system was developed by HNEI and Powertech to dispense up to 90% of the hydrogen stored in the HTT in order to reduce transportation costs by not having to return half-filled trailers to be refilled at NELHA.

Figure 7. MTA Boost Compressor Fueling Post.

Hele-On 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. During this reporting period, the fuel cell power system was upgraded by replacing the original 30 kW Hydrogenics fuel cell with a new state-of-the-art 40 kW U.S. Hybrid fuel cell. During commissioning, the fuel cell produced 46kW, a 15% improvement, and the range increased from 200 miles to 300 miles, a 50% improvement.

Figure 8. Hele-On 29-Passenger FCEB.

Onboard hydrogen is stored in composite carbon fiber cylinders located under the bus with a capacity of 20 kg. The fuel cell power system is integrated with two 11 kWh A123 Lithium-ion battery packs to provide motive power to a 200 kW electric drive system. U.S. Hybrid also replaced batteries with the new technology A123 batteries using U.S. Hybrid internal funding. At cruising speed, the fuel cell maintains the battery state of charge within a range that supports the long-term health of the battery.

During deceleration, the electric motor acts as a generator sending power back into the battery ("regenerative braking"). This contributes to overall system energy efficiency and improves bus mileage. 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 also acquired by the MTA from Hawai'i Volanoes National Park (HAVO). These buses were converted by U.S. Hybrid and are of similar design to the 21-passenger FCEB. Onboard hydrogen capacity is 10 kg giving a projected range of 100 miles. These buses are being upgraded with 40 kW U.S. Hybrid fuel cells and A123 Lithium-ion batteries using funding provided by the County of Hawai'i.

Figure 10. HAVO 19-Passenger FCEB.

Figure 11 is a conceptual design of the hydrogen fueling dispensing system 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.

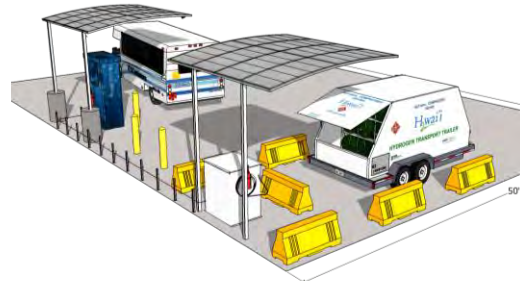


Figure 11. Proposed MTA Fueling Dispensing Station.

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

Figure 12. MTA Site with Fueling Dispenser.

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 65kg/day (2.7 kg.hr). This corresponds to approximately 78 to 88 kwh/kg of compressed hydrogen. The breakdown of the observed power usage is provided in Table 1 on the following page. This represents the largest single load on the NELHA research campus grid.

Table 1. NELHA Hydrogen Station Observed Power Usage

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

In 2022, HNEI also assisted the County of Hawaiʻi MTA in the development of their proposal resulting in a grant for $23 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 "the technical assistance of HNEI helped the MTA win this recent grant award".

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 Source: 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

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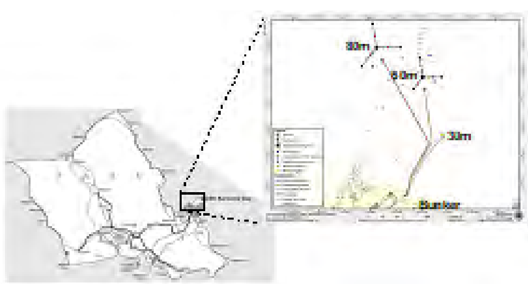
Last Updated: November 2022

G1: Research Support to the U.S. Navy Wave Energy Test Site

OBJECTIVE AND SIGNIFICANCE: Wave energy has potential to address global renewable energy goals, yet it poses daunting challenges related to commercializing technologies that must produce cost-competitive electricity while surviving the energetic and corrosive marine environment. The nascent commercial wave energy sector is thus critically dependent on available test infrastructure to advance development of wave energy conversion (WEC) devices and related technologies. For this reason, the U.S. Navy established the Wave Energy Test Site (WETS) in the waters off Marine Corps Base Hawaiʻi (shown below) as the United States' first grid-connected site, completing the buildout in mid-2015. WETS consists of test berths at 30m, 60m, and 80m water depths, and can host point absorber and oscillating water column (OWC) devices to a peak power of 1 MW.

HNEI provides key research support to this national effort in the form of environmental monitoring, independent WEC device performance analysis, and critical marine logistical support. The results achieved at WETS have far reaching impacts in terms of advancing wave energy globally.



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

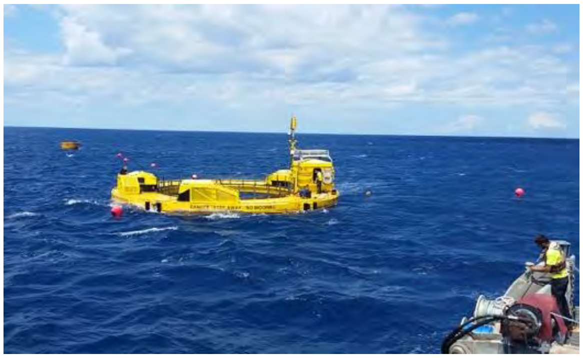
In Summer 2021, NAVFAC granted HNEI an additional $6M to continue this core support to WETS, and to expand research related to smaller-scale WECs for offshore, non-grid-connected applications of wave energy. This will include: 1) an examination of the potential for existing WETS infrastructure to support the creation of an offshore test and demonstration node, including subsea power storage as well as communications and power interfaces that would allow small WECs to power applications such as autonomous undersea vehicle (AUV) recharge, 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. 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.

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

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

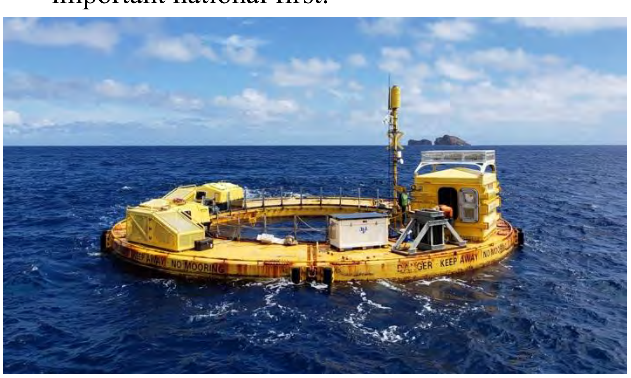
- Northwest Energy Innovations (NWEI) deployed Azura device at 30m berth Jun 2015 to Dec 2016.

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



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

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



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

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

Issues stemming from COVID, funding, and technical challenges have delayed planned WEC deployments over the past year, but three deployments are currently 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 Hawaiʻi in October 2021, and is now expected to be deployed in early 2023. 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 will follow in late 2022.

2. Deployment of the C-Power SeaRay WEC. This will be a stand-alone (not grid-connected) deployment of a small, 1kW, device that will feed power to a subsea acoustic sensing system from the company Biosonics, as well as other environmental sensors. Deployment readiness is expected in late January 2023.

3. Deployment of the Ocean Energy (Ireland) OE35 WEC at the 60m berth. This device has been in Hawai‘i since December 2019, and underwent drydock repairs in Aug/Sep 2022, after extensive delays. It should be ready for deployment to WETS in the spring of 2023.

Looking ahead, we expect WEC deployments from C-Power (a larger version of the SeaRay device), Northwest Energy Innovations (a much larger version of Azura), and Oregon-based Aquaharmonics – in the 2024-2025 timeframe.

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

Contact: Patrick Cross, pscross@hawaii.edu

Last Updated: November 2022

G2: The Hawai‘i Wave Surge Energy Converter (HAWSEC)

OBJECTIVE AND SIGNIFICANCE: The objective of the Hawai‘i Wave Surge Energy Converter (HAWSEC) project, funded by the Department of Energy, 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 Hawai‘i, the U.S., and beyond.

BACKGROUND: HNEI has been involved in supporting research and testing objectives at the U.S. Navy's Wave Energy Test Site (WETS), off Marine Corps Base Hawai‘i, since 2010, with funds from both the U.S. Department of Energy (DOE) and the U.S. Navy (Naval Facilities Engineering Command – NAVFAC). Through this involvement, HNEI has gained valuable practical experience associated with real-world deployment and operation of WECs in this first-of-its-kind in the U.S. grid-connected test site. Additionally, through numerical modeling of WEC dynamics and mooring systems in support of WETS test objectives and WEC developers, HNEI has accumulated key design insights and numerical modeling experience related to WEC design.

The HAWSEC concept is based on the oscillating wave surge converter (OWSC), or flap-type WEC. Such systems rely on the surge motion of the waves close to shorelines, where wave direction becomes more consistent than offshore. The flap moves back and forth in the waves and drives hydraulic cylinders to pump water through a hydro turbine to generate electricity. Its inherent scalability could support smaller-scale generation for isolated communities or islands, or larger-scale devices (likely deployed in arrays) to generate power to feed into coastal power grids. A rendering of our conceptual flap is shown in Figure 1.

We will explore both a high-head/low-flow and a low-head/high-flow hydraulic system, utilizing the same flap, in the first half of the project, ultimately settling on an optimized configuration (with a hydro turbine selected to best align with the optimized head and flow) before scaling up for additional testing in the latter stages of the project.

Figure 1. Rendering of the HNEI HAWSEC system.

PROJECT STATUS/RESULTS: This nominally three-year 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 O‘ahu;
3. Controlled tank testing of the small-scale system at Oregon State University's (OSU) Hinsdale wave basin;
4. Validation of numerical modeling with test results from OSU;
5. Numerically scaling up to medium scale, nominally a 3m x 3m flap, and completing a buildable design of the HAWSEC at this scale;
6. Undergoing a Go/No-Go decision with DOE;
7. Fabrication of a full medium-scale system, including flap and hydraulics;
8. Controlled tank testing of the medium-scale device at the University of Maine's test flume; and
9. Validation of medium-scale numerical models with test data from Maine, and modeling and performance prediction for a full-scale version of HAWSEC.

Task 1 numerical modeling is complete, and the smaller-scale flap system was designed and fabricated in 2021. A hydraulic bench test setup has been completed in our lab on the U.S. campus.

Nearshore testing of the flap in local waters (at Makai Research Pier) was conducted in May of 2022 (Figure 2 on the following page).

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).

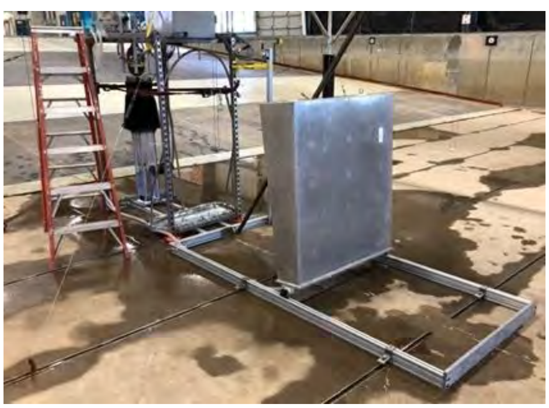


Figure 3. Controlled wave basin testing at OSU.

Substantial procurement challenges have delayed our timeline considerably and we now expect complete Phase I of the project in September 2023. Recent testing has shed valuable light on the hydrodynamic characteristics and power performance of our WEC and will be crucial in validating numerical models at the smaller scale and scaling these results up to a larger-scale device for subsequent testing in 2024.

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 2022

H1: Asia Pacific Regional Energy System Assessment (APRESA)

BACKGROUND: In August 2017, HNEI was awarded a five-year 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 select locations throughout 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. During the first five years of APRESA, HNEI established substantive strategic partnerships with national, regional, and local jurisdictions, as well as private and public stakeholders including utilities, universities, and other research and international aid and development entities such as the World Bank (WB), Asian Development Bank (ADB), 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 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 include Fiji, Kiribati, Republic of Marshall Islands, Federated States of Micronesia, Nauru, Palau, Samoa, Solomon Islands, Tonga, Tuvalu, and Vanuatu under WB funding, with these partnerships initially made possible through APRESA regional support activities. The criteria for selection of jurisdictions include those with significant rates of projected demand growth requiring rapid energy system expansion and transformation; strategic trade and geopolitical opportunities to the United States; potential to integrate renewable energy technologies; and a collaborative environment to conduct the work.

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

USAID partner country governments 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 proposes to utilize continued APRESA funding to extend the efforts in the current countries and to expand this work to other countries, regions, and DOD facilities of interest. 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.

PROJECT STATUS/RESULTS: A number of select projects initiated under the APRESA award are summarized below. Many of these are also described in more detail in separate project summaries included in this Appendix.

Biomass Energy Demonstration (Thailand)
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 and is being installed and evaluated in an existing micro-grid operated at Chiang Mai Rajabhat University. Extended tests will evaluate feedstocks and their preparation, identify maintenance requirements and practices, and develop system control strategies for interfacing with the intermittency of other micro-grid components.

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 can be converted to renewable diesel and sustainable aviation fuel. Seed meal and pod fiber are processing coproducts with potential value as animal feeds and energy/bioproduct feedstocks, respectively. Under this project, cost estimates for pongamia production are being developed for farm gate prices of harvested seed-in-pod to inform design of pongamia based value chains.

Postdoctoral Training in Sustainable Aviation Fuel
APRESA funds have supported Dr. Quang Vu Bach's participation in a research program evaluating sustainable aviation fuel production systems for tropical environments. Current activities include evaluation of biomass resources derived from urban solid waste and their suitability as feedstocks for thermochemical gasification systems. The synthesis gas product can be subsequently converted with Fischer-Tropsch synthesis to sustainable aviation fuel. The aviation industry (civilian and military) faces significant greenhouse gas challenges due to dependence on petroleum jet fuels and limited opportunity for electrification.

EGAT Renewable Integration Study (Thailand)
On February 28, 2018, the Electricity Generating Authority of Thailand (EGAT) held a ceremony to sign a multi-year Memorandum of Understanding (MOU) with HNEI. The MOU terms of reference include education, training, workshops, and exchange programs (study tours or site visits) under topics, such as "strengthening the operation capacity to support renewable energy integration into the power system." Under this MOU, HNEI's Grid System Technologies Advanced Research Team (Grid*START*) built upon its prior work with EGAT, developing and calibrating a high-fidelity production cost model of the Thai power grid in PLEXOS, and applied the model to assess the impact on the Thai power grid of alternative high penetration distributed PV scenarios over the next five- to ten- year horizon. With COVID-19 travel restrictions to Thailand now lifted, HNEI is engaged with EGAT to scope follow-on analysis using the PLEXOS Thai power grid model, such as evaluation of carbon reduction pathways for the country, given recent targets set by the Thai government. EGAT recently purchased a license for the PLEXOS software which enables an opportunity for deeper collaboration in grid analytics ahead. This working relationship is described in more detail in Appendix H2.

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 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 the Spring of 2020, staff from HNEI's Grid*START* have taken the lead in delivering this training program designed to accept two classes of PEA interns annually. Each class of six engineering interns participates at HNEI in an eight-week curriculum of combined lectures (40 hours) and team-oriented deep immersion in custom "mini-project" research, development, and test endeavors tailored to the learning needs of working utility engineers. COVID-19 travel restrictions resulted in class postponements and a partial transition to online learning in the 2020-2021 timeframe. However, with the recent lifting of travel restrictions, the first and second 2022 class of PEA interns were trained at HNEI from June to August and

August to October, respectively. Each class of interns was split into two sub-groups working simultaneously on different mini-project topics: 1) optimization of virtual power plant (VPP) dispatch and demand response (DR) applications; 2) improvement of electric vehicle (EV) energy consumption estimation approach for use in EV charge/discharge optimization algorithm; 3) PV hosting capacity methodology and assessment; and 4) optimized microgrid system design. Overall, the training program provided PEA engineers with enhanced technical knowledge of distributed energy resource (DER) technologies, EV applications and microgrids. This work is described in more detail in Appendix H5.

Technical Support for Development of BESS Technical Standards for Thailand

The objective of this effort was to deliver technical assistance to Thailand's Office of Energy Regulatory Commission (OERC) in its ultimate adoption of codes and regulations for battery energy storage system (BESS) applications in Thailand. Through leveraged partial funding by USAID Clean Power Asia (CPA), HNEI Grid*START* provided expert advice to OERC and Thai stakeholders, culminating in the delivery of a comprehensive guide and roadmap to develop BESS technical codes and standards for Thai regulatory action. Following the first Stakeholder Focus Group held in August 2020, a Final Stakeholder Consultation Workshop was held in Bangkok on February 18, 2021. HNEI presented online the final draft of the BESS technical standards report to OERC, with Thai electric utilities and numerous energy sector stakeholders in attendance. Stakeholder feedback was incorporated into the final deliverable "*Guidelines for Developing BESS Technical Standards in Thailand*," which was submitted to USAID CPA on March 29, 2021, for delivery to OERC. Based on this work, HNEI was engaged in 2022 to develop a regulatory framework for adoption of BESS applications for the Philippines' Energy Regulatory Commission under funding from USAID.

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

The MOU establishes a framework for multi-year collaboration amongst HNEI and Chula engineering faculty and graduate students on a range of activities exploring approaches, methodologies, tools, techniques, systems, and policies that lead to enhanced resilience and energy reliability while enabling a clean energy transition through grid modernization and smart grid initiatives. Active collaborative endeavors included continuing work on the Chulalongkorn Smart Campus Project. This collaboration, established to build joint research and development capacity in grid modernization technologies, centers on field deployment of HNEI Grid*START*'s Advanced Real-time Grid Energy Monitor System (ARGEMS), integrated with other intelligent grid-edge technologies in Chulalongkorn's Smart Campus Project. To date, two ARGEMS devices were shipped to Chulalongkorn University. The first device has been operating in a lab setting for over a year, and the second device is now installed on a campus building transformer. Additional devices were prepared for final configuration and shipment. In advance of deployment at Chulalongkorn University, HNEI improved the ARGEMS documentation and developed software to enable remote firmware updates, device configuration, and testing to support the use of a new type of current transducer (Rogowski coil) needed for the Smart Campus Project field installation.

Mapping of Renewable Energy Sector Innovation System (Vietnam)

Under this effort, HNEI is providing financial support and guidance, to the National Institute for Science and Technology Policy and Strategy Studies (NISTPASS) to map the innovation system in the renewable energy (RE) sector in Vietnam. While the development of renewable energy resources in Vietnam is a government priority, there is lack of clarity about the role of many organizations in Vietnam impacting energy development and the relationship between them. An objective of this work is to identify which Vietnamese stakeholders in the RE sector can benefit from further policy and institutional support.

With the rapidly growing industrialization and modernization of the economy, energy demand in Vietnam has increased rapidly between 2016-2020 and is predicted to increase by eight percent per annum through 2030, resulting in a four-fold increase in total electricity demand compared to 2014. To meet the aggressive government goals associated with RE innovation, the project is focused on identifying relevant organizations in the sector and understanding how they interact with each other and as a system. The analysis will involve an exhaustive review of energy producers, energy consumers, business systems, educational and research systems, policies, regulations and statutes, and infrastructure developers.

In 2022, NISTPASS completed interviews with key players in the four groups of stakeholders in the renewable energy sector in Vietnam, focusing on solar and wind energies. The interviews have yielded 21 overall trends and findings ranging from opportunities in the supply side of the sector innovation system to the impacts of environmental factors and the COVID-19 pandemic. NISTPASS is currently preparing a final report summarizing results of RE innovation mapping for Vietnam and will announce plans for an international workshop/conference in Honolulu during the Spring of 2023 to review the results and explore next steps. A summary report of the outcome of the international workshop and the issuance of two publications containing research results in both the Vietnamese and English language will conclude the project. The project began in August of 2019 and is scheduled for completion in September of 2023. This work is described in more detail in Appendix H3.

Renewable Energy Integration Support in Vietnam
The USAID Vietnam Low Emission Energy Programme (V-LEEP) under the leadership of Deloitte Consulting has been working closely with relevant agencies in Vietnam's Ministry of Industry and Trade (MOIT), the Electricity and Renewable Energy Authority (EREA), Electricity Regulatory Authority of Vietnam (ERAV), and the Institute of Energy (IEVN) to study and enable a functional and competitive regulatory framework and conditions which support an increase of renewable energy generation and consumption. HNEI partnered with the National Renewable Energy Laboratory (NREL) to support V-LEEP with expertise in variable renewable energy integration modeling and advanced power system planning for Vietnam's Power Development Plan (PDP-8) efforts. This initiative, which was extended an additional year, allowed HNEI to continue its partnership with NREL to support V-LEEP with further grid modeling and stakeholder training, building capacity in the use of advanced tools and methodologies in the Vietnam Power Development Plan-8 process. HNEI Grid*START*'s support and partnership with Deloitte Consulting is continuing with the recent launch of the V-LEEP II program, which Deloitte again leads and builds upon its preceding V-LEEP program success.

Saigon Energy Hub (SEHub) Support
HNEI is supporting the Center for Urban Studies (CRUS) in the development of an online and offline energy-efficiency and renewable energy education platform to offer energy themed workshops on energy technologies and platforms. Ten public workshops will be presented live and online to the community of Ho Chi Minh City to advance public understanding and drive energy policy. The project will continue through July 2024. This work is described in more detail in Appendix H4.

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 recent 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 2023.

USAID South East Asia's Smart Power Program (SPP) Regional Collaborative Support
A Letter of Collaboration initiated by Deloitte Consulting, the prime contractor for the new USAID South East Asia's Smart Power Program (SPP), was signed with HNEI on October 27, 2022. The SPP is USAID's regional successor program to its earlier Clean Power Asia (CPA) program in which HNEI's Grid*START* delivered both collaborative (APRESA funded) and CPA funded support over the prior four years. SPP is a five-year program intended to expand energy capacity through deployment of advanced

energy systems, increase clean energy investment across the region's energy sector, and improve regional energy trade to ensure secure and market-driven energy sectors that sustain economic growth. The program will leverage bilateral and multilateral partnerships, support regional initiatives, accelerate cross-border interconnection and power trade, and create centers for training of energy practitioners to develop solutions that will help Southeast Asian countries become self-reliant and achieve their sustainable development aspirations. USAID SPP plans to implement numerous activities, including by example establishing a Center for Competitive Procurement (CCP), conducting a resiliency assessment of ASEAN power utilities, and other capacity development undertakings to support ASEAN utilities. Deloitte Consulting and HNEI Grid*START* anticipate collaboration where there are opportunities for leveraging comparative advantages of USAID SPP and HNEI across all of SPP's task areas, including utility modernization, demand-side management/demand response ("DSM/DR"), energy innovation and emerging trends, competitive procurement, power trade, and grid integration. Initial tasks for collaborative work are being scoped, with work activities to be launched first in Laos and Thailand in January 2023.

Technical Interconnection Requirements for Solar and Wind Projects in Laos
Starting in 2018, HNEI, in a partnership with USAID Clean Power Asia (CPA), drafted interconnection grid codes and supported power purchase agreement (PPA) structure and terms development for Laos' first market-based competitive solar pilot auction. Based on this work, Électricité du Laos (EDL), the Laos grid operator, requested extended support from HNEI to develop interconnection grid codes for distributed PV and utility-scale solar and wind projects, a foundational need to enable uptake of solar and wind resources into the Laos power grid. Staff from HNEI's Grid*START* commenced work in 2020 on two key deliverables: 1) *Électricité du Laos Distributed Solar Photovoltaic Generating Facility Interconnection Standards* (Dec 2020); and 2) *Électricité du Laos Inverter-based Generating Facility Transmission Interconnection Standards* (Jan 2021). These deliverables were submitted and presented jointly by HNEI and USAID CPA to EDL and the Lao Ministry of Energy and Mines (MEM) in March 2021. As these proposed technical standards are now being applied in Laos, the new USAID Southeast Asia's Smart Power Program (SPP) has requested collaborative support from HNEI Grid*START* to deliver further training on these standards to EDL, Laos MEM, and energy project developers. Activity scoping is underway, with a launch meeting for this initiative with USAID SPP, EDL, and MEM planned for January 2023.

Support to the USAID Energy Secure Philippines (ESP) Program
In 2019, HNEI Grid*START* delivered technical and capacity building support in collaboration with USAID CPA to assist the Philippines Department of Energy (PDOE) to prepare and present its Department Circular (DC) for "*Promulgating Policies to Enhance Customers' Participation in the Philippines' Net-Metering Framework*." In 2020, PDOE issued a new Net-Metering Policy which, while maintaining a 100 kW limit on system capacity, removed the Distribution Impact Study fee imposed by distribution utilities on Net-Metering applicants.

HNEI is continuing its support of 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 has been asked to develop a set of rules for an "off-grid" net energy metering (NEM) program tailored to small, rural area grid systems in the Philippines, that allows customers to sell excess distributed generation to the DUs of these small island systems that are not connected to the country's transmission network. HNEI is also collaborating with USAID ESP and the ERC to establish a battery energy storage system (BESS) regulatory framework for the Philippines, including: 1) streamlined rules for BESS interconnection; 2) guidelines for BESS technical codes and standards; 3) cost recovery mechanisms for utility-owned BESS; and 4) third-party-owned BESS for ancillary services. With the loosening of travel restrictions, HNEI conducted in-person presentations and regulation drafting workshops to the ERC in Manila during the second half of 2022 on: 1) HNEI's draft NEM report; 2) HNEI's draft BESS report; and 3) the ERC's draft BESS regulation for the Philippines. This work is assisting the ERC in fulfilling the mandate set by the PDOE. This work is described in more detail in Appendix H9.

ASEAN Interconnection Masterplan Study (AIMS) III Support
As a basis for assessment, regional planning, and development of a prospective integrated ASEAN Power Grid, the ASEAN countries – led by the Head of ASEAN Power Utilities/Authorities (HAPUA) – have conducted the ASEAN Interconnection Master Plan Study (AIMS). Building upon this foundational work, the latest AIMS III analysis has evaluated ASEAN power market integration through the grid connection of renewable energy and power trade. HNEI's Grid*START* served as a core member of the technical review group (TRG) comprised of international experts (including NREL and IEA), which reviews and provides guidance on the scope, data collection, assumptions, and execution of the AIMS III study. The AIMS III project concluded in September 2021 with the end of the USAID CPA program. HNEI may support follow-on work in ASEAN countries that builds upon the AIMS III results as part of its newly formed collaboration with USAID's SPP described above.

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

Funding Source: Office of Naval Research

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Last Updated: November 2022

Hawai‘i Natural Energy Institute Research Highlights

Appendix H: International

H2: EGAT Renewable Integration Study

OBJECTIVE AND SIGNIFICANCE: HNEI is collaborating with the Electricity Generating Authority of Thailand (EGAT), the utility responsible for generation and transmission of power throughout Thailand, to conduct a renewable energy (RE) integration study for the country and enhance the professional capacity of its engineers in advanced study methods and grid simulation tools.

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

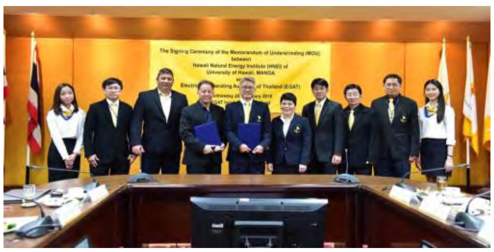

Figure 1. HNEI-EGAT MOU signing ceremony in 2018.

Activities include constructing a high-fidelity production cost model of the Thai power grid and assessing the operational and economic impact of high penetration solar photovoltaic (PV) scenarios over a five- to ten-year planning horizon. The project is intended to empower EGAT engineers to perform such analyses on their own going forward.

High levels of customer-sited distributed PV pose grid challenges due to its intermittency and variability and the limited flexibility of legacy power systems to respond to and balance resulting system net load. With high levels of RE, many conventional generation resources are shut down or dispatched to minimum operating levels to “make room” for the new RE generation, with remaining online units needing to ramp more quickly and frequently over a wider operating range to counter the variability and uncertainty of RE production. The cost of dispatched generation may also increase due to less efficient operation and the need for increased operating reserves. However, depending on the level of penetration, distributed PV may alleviate transmission congestion in some areas by collocating generation with load. While Thailand’s moderate level of PV and wind resources today do not yet pose serious operating concerns, Thai energy policy is supporting rapid near-term market growth in RE additions. EGAT’s swift action to build the tools and capacity to evaluate high penetration RE scenarios is a necessity.

PROJECT STATUS/RESULTS: HNEI Grid*START* and EGAT built and calibrated a high-fidelity production cost model of the Thai power grid in PLEXOS. The PLEXOS model includes seven nodes – each node representing a region of Thailand with inter-nodal transmission transfer limits modeled.

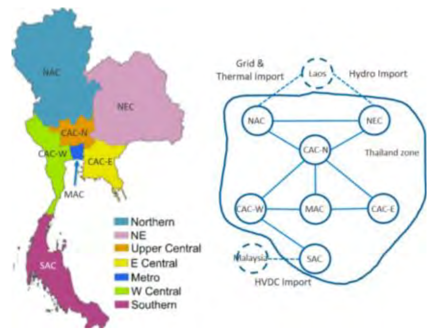

Figure 2. Thailand PLEXOS “bubble model” topology.

Time series PV and wind data sets for all existing RE and future high penetration RE cases were developed. Analysis of base, low, medium, and high distributed PV scenarios were completed with conditions of operational concern identified, including excess energy production potential during low load periods, transmission congestion, reserve shortages, high number of thermal unit starts, etc. COVID-19 travel restrictions slowed the project over the past year. HNEI Grid*START* is working to update the focus of the analysis given Thailand’s current policy objectives, including carbon neutrality.

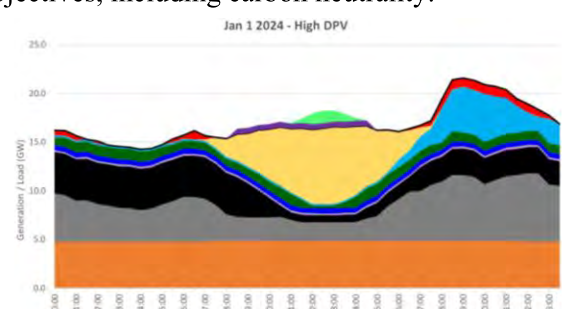

Figure 3. Thailand 2024 low system load day with high distributed PV (yellow) and excess PV energy (green).

Funding Source: Office of Naval Research

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Last Updated: November 2022

H3: Mapping of Renewable Energy Sector Innovation System

OBJECTIVE AND SIGNIFICANCE: Under funding of its Asia Pacific Regional Energy System Assessment (APRESA) program (see Appendix H1), HNEI is providing financial support and guidance to the National Institute for Science and Technology Policy and Strategy Studies (NISTPASS) to map the innovation system in the renewable energy (RE) sector in Vietnam. While the development of renewable energy resources in Vietnam is a government priority, there is lack of clarity about the role of many organizations in Vietnam impacting energy development and the relationship between them. An objective of this work is to identify which Vietnamese stakeholders in the RE sector can benefit from further policy and institutional support.

BACKGROUND: With rapidly growing industrialization and modernization of the economy, energy demand in Vietnam has increased rapidly between 2016-2020 and is predicted to increase by eight percent per annum through 2030 resulting in a four-fold increase in total electricity demand compared to 2014. To meet the aggressive government goals associated with RE innovation, the project is focused on identifying relevant organizations in the sector and understanding how they interact with each other and as a system. The analysis will involve an exhaustive review of energy producers, energy consumers, business systems, educational and research systems, policies, regulations and statutes, and infrastructure developers. The project began in August of 2019 and is scheduled for completion in September of 2023.

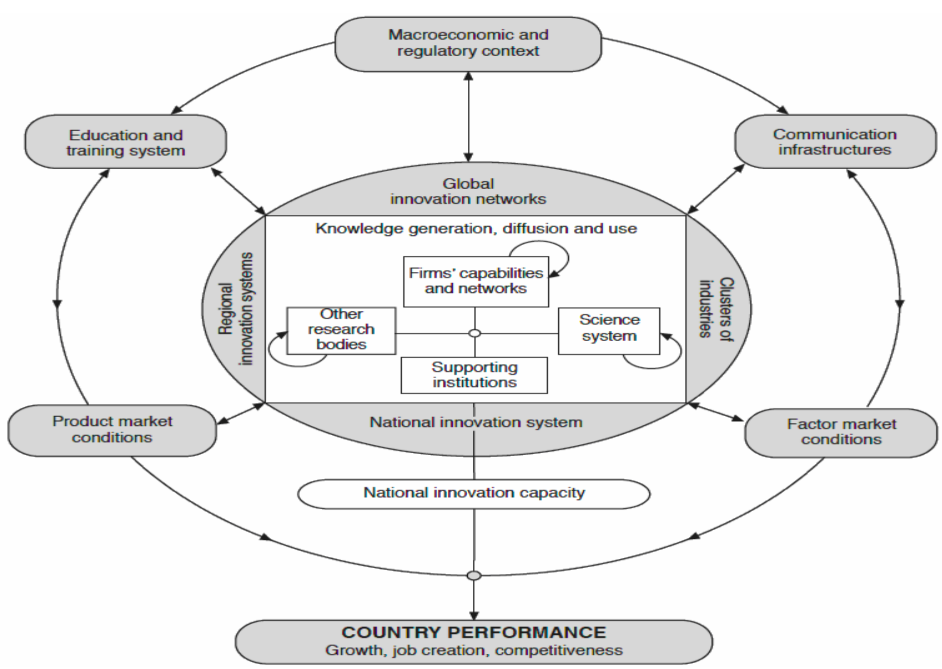
PROJECT STATUS/RESULTS: In 2022, NISTPASS completed interviews with key players in the four groups of stakeholders in the renewable energy sector in Vietnam, focusing on solar and wind energies. The interviews have yielded 21 overall trends and findings ranging from opportunities in the supply side of the sector innovation system to the impacts of environmental factors and the COVID-19 pandemic.

NISTPASS is currently preparing a final report summarizing results of RE innovation mapping for Vietnam and will announce plans for an international workshop/conference in Honolulu during the Spring of 2023 to review the results and explore next steps. A summary report of the outcome of the international workshop and the issuance of two publications containing research results in both the Vietnamese and English language will conclude the project.

Funding Source: Office of Naval Research

Contact: Mark B. Glick, mbglick@hawaii.edu

Last Updated: November 2022



H4: Saigon Energy Hub (SEHub) Support

OBJECTIVE AND SIGNIFICANCE: The purpose of the Saigon Energy Hub (SEHub) project is to install an offline and online platform to promote renewable energy (RE) and energy efficiency (EE) in Ho Chi Minh City by hosting a series of public energy-educational forums to raise community awareness as well as 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 ten (10) publicly accessible energy-related workshops through the workshop platforms.

BACKGROUND: Among the objectives of the Hawaiʻi Natural Energy Institute 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 an agreement with the Office of Naval Research, HNEI is supporting Ho Chi Minh City's local non-governmental organization, the Center for Regional and Urban Studies (CRUS) to design and implement the 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 CRUS, 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.

CRUS is currently in the process of outfitting two meeting spaces in the The Ho Chi Minh City Union of Science and Technology Associations (HCM-USTA) Building 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 ten (10) live and online energy-related workshops. CRUS will develop and present for approval the ten 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.

The project is currently in development and will continue through December 2024.

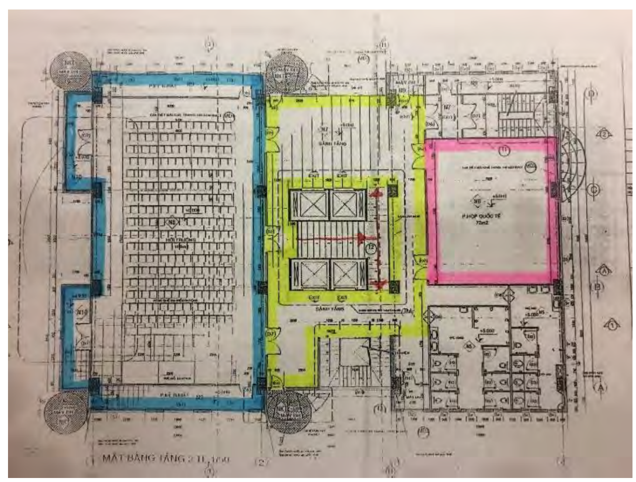


Figure 2. Conference room layout of the HCM-USTA Building.

Funding Source: Office of Naval Research

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Last Updated: November 2022

H5: 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 EV charging applications for engineers from the Provincial Electricity Authority of Thailand (PEA) — 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).

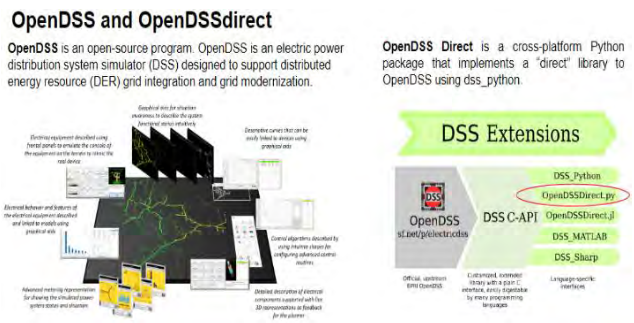

Figure 1. Sample of the teaching materials.

BACKGROUND: Since Spring 2020, staff from HNEI's Grid*START* has taken the lead in delivering this training program designed to accept two classes of PEA interns annually. Each class of six engineering interns participates at HNEI in an eight-week curriculum of combined lectures (40 hours) and team-oriented deep immersion in custom "mini-project" research, development, and test endeavors tailored to the learning needs of working utility engineers.

With an emphasis on applications for energy distribution systems, a series of lectures cover subjects such as renewable energy integration and smart grid technologies. Examples of mini-project endeavors include developing new controls applications residing on field-deployed bidirectional electric vehicle (EV) chargers installed on the UH Mānoa campus, analyzing PV hosting capacity for medium and low-voltage networks, studying the energy management of a virtual power plant, and optimizing microgrid design and system operation.

PROJECT STATUS/RESULTS: COVID-19 travel restrictions resulted in class postponements and a partial transition to online learning in the 2020-2021 timeframe. However, with the lifting of travel restrictions in 2022, two classes of PEA interns were trained at HNEI from June to August and August to October, respectively. Each class was split into two sub-groups working simultaneously on different mini-project topics: 1) optimization of virtual power plant (VPP) dispatch and demand response (DR) applications; 2) improvement of EV energy consumption estimation approach for use in EV charge/discharge optimization algorithm; 3) PV hosting capacity methodology and assessment; and 4) optimized microgrid system design. Overall, the program provided PEA engineers with enhanced technical knowledge of distributed energy resource (DER) technologies, EV applications and microgrids.

In the VPP mini-project, PEA engineers analyzed and demonstrated the economic dispatch of several customer-sited PV and BESS resources, in aggregate delivering customer bill savings and utility desired energy/power services. In the EV mini-project, the interns investigated means to enhance an EV energy consumption estimation algorithm under differing vehicle, road and weather conditions. In the PV hosting capacity mini-project, they learned best-practice methods to determine the capacity of a distribution circuit to accept distributed PV systems, and applied their learning to determine the hosting capacity of an actual PEA medium- and low-voltage distribution circuit. Finally, in the microgrid mini-project, the interns sized and assessed the feasibility of several prospective microgrid sites in Thailand (two factories, a school, and the PEA headquarters building) using XENDEE, a microgrid design and techno-economic optimization platform.

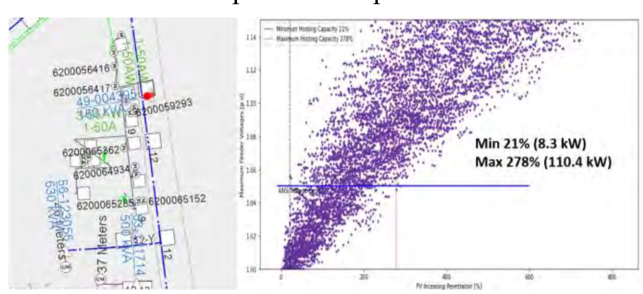

Figure 2. PV hosting capacity simulation on a PEA's distribution grid in Pattaya City, Chonburi, Thailand.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2022

Hawaiʻi Natural Energy Institute Research Highlights

Appendix H: International

H6: USAID Papua New Guinea Electrification Partnership (PEP) Activity

OBJECTIVE AND SIGNIFICANCE: HNEI is providing technical assistance under subcontract 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 which aims to support PNG's enhanced electric connectivity and its goal of connecting 70% of its population to electricity by 2030. Through the expansion of reliable and affordable electricity, PEP will help advance inclusive growth, development, and empowerment in communities throughout the country.

Figure 1. Ela Beach, Port Moresby, PNG.

BACKGROUND: In November 2020, the U.S. government launched the five-year, $57 million USAID-PEP program to support PNG in increasing reliable electric connectivity to its people. HNEI is contributing to this partnership by supporting RTI to: 1) improve the financial viability and operational efficiency of the country's electricity provider, PNG Power Limited (PPL); 2) develop viable off-grid electrification models; and 3) improve PNG's energy regulations.

PROJECT STATUS/RESULTS: In particular, HNEI is supporting RTI on end-to-end utility transformation of PPL by improving competitive procurement via focus group discussions with selected government and private sector representatives and supporting the conduct of due diligence on the existing independent power producer pipeline. HNEI is supporting RTI in its effort to develop viable off-grid electrification models, including developing and executing a private sector engagement strategy for off-grid companies, building a portfolio of viable sites for off-grid electrification, and participating in stakeholder groups already working on off-grid regulations in PNG. Finally, for the demonstration of measurable improvement in PNG's energy regulator, the National Energy Authority (NEA), HNEI's Grid*START* is assisting RTI with improving the national regulatory framework for off-grid electrification and a process for stakeholder engagement to inform and implement enabling policies and regulation.

Figure 2. Rural villages in PNG.

HNEI Grid*START*'s support of USAID-PEP to date has spanned a range of tasks, including: 1) reviewing, commenting on, and editing the draft PNG Off-Grid Regulation and underlying Off-Grid Guidelines; 2) reviewing and commenting on the appropriateness for PNG's National Institute of Standards and Industrial Technology (NISIT) to adopt certain IEC standards regarding renewable energy and hybrid systems for rural electrification; 3) participating in numerous online meetings and workshops with stakeholders including RTI, USAID-PEP, NEA, NISIT, and NARUC; and 4) conducting virtual training on HOMER software to support the modeling/analysis of a mini-grids/off-grid power systems in remote areas of the country.

Most recently, HNEI has reviewed and recommended updates to PNG's Third-Party Access Code, Electricity Industry Regulations, and Grid Code for transmission-level interconnections, and also recommended interconnection standards for inverter-based resources connected at the distribution level. In-person presentations of HNEI's recommendations will be delivered in Port Moresby to RTI, USAID PEP, NEA, PPL and PNG independent power producers in November 2022.

Funding Source: USAID-PEP

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Last Updated: November 2022

H7: USAID Scaling Up Renewable Energy II (SURE II)

<u>OBJECTIVE AND SIGNIFICANCE</u>: HNEI via its Grid System Technologies Advanced Research Team (Grid*START*) is serving as a technical resource to the United States Agency for International Development (USAID) Scaling Up Renewable Energy II (SURE II) project. The project objective is to assist partner countries in increasing the level of renewable energy and new technology into their electricity mixes using a cost-effective, reliable, and environmentally-friendly methodology that enables countries to achieve greater self-reliance. Its expected outcomes include: increased renewable energy capacity, improved grid integration of renewable energy, increased competition for generation capacity, and dissemination of green procurement practices in project partner countries worldwide.

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

SURE II provides support under the following six task areas:

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

<u>PROJECT STATUS/RESULTS</u>: Under the leadership of the prime contractor, Tetra Tech, Inc., HNEI is engaged in Tasks 1, 2, and 3 to support partner countries seeking assistance under SURE II. HNEI will leverage its experience in the effective planning, procurement, and integration of renewable energy resources into power systems to provide among other services capacity-building training to partner countries.

In particular, HNEI will deliver the following for the supported tasks:

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

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

The SURE II project completed its second year of the five-year project. HNEI is ready to deliver technical support as the project heads into its third year.

Figure 1. SURE program partner countries. (Cited from SURE 2020 Annual Report).

Funding Source: USAID SURE II

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Last Updated: November 2022

H8: Developing Renewable Energy Storage System for the Pacific Island Countries

<u>Objective and Significance</u>: HNEI via its Grid System Technologies Advanced Research Team (Grid*START*) is providing technical assistance under contract to the World Bank for its *Developing Renewable Energy Storage System for the Pacific Island Countries (PICs)* project. The project objective is to support eleven PICs, namely Fiji, Kiribati, Republic of Marshall Islands (RMI), Federated States of Micronesia (FSM), Nauru, Palau, Samoa, Solomon Islands, Tonga, Tuvalu and Vanuatu, in designing a regional Battery Energy Storage Systems (BESS) policy framework and guidelines with underlying technical/commercial assessments for each PIC to support private sector participation in BESS development.

<u>Background</u>: The PICs, each of which have set high power sector renewable energy (RE) penetration targets, face challenges inherent with the integration of RE resources on isolated island systems including addressing energy insecurity and price volatility due to heavy reliance on costly imported fossil fuels, challenging grid operations with related system reliability impacts, and increasing threats to energy resilience due to climate change. Energy storage systems, BESS in particular, will be key in achieving high RE penetration targets and mitigating PIC energy challenges ahead.

For PIC island grids, estimating grid-wide BESS requirements (i.e., aggregate BESS capacity (MW) and energy (MWh)) as a function of increasing variable renewable energy (VRE) penetration, can generally be grouped into four sequential phases of increased BESS deployment: 1) ~0-20% VRE, for grid services and renewable enablement; 2) ~20-30% VRE, for generation capacity deferral and/or fossil unit retirement; 3) ~30-70% VRE, for excess RE curtailment mitigation via energy shifting; and 4) ~70-90+%, for long duration energy shifting.

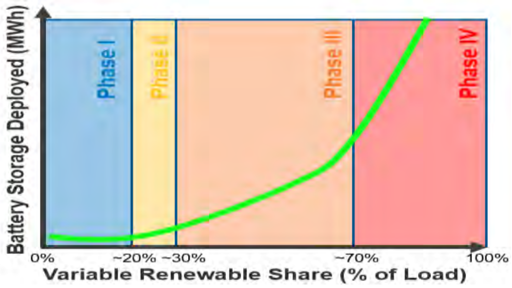

Figure 1. Four phases of BESS deployment on island power grids.

In phase IV, island grid systems may be able to reach very high RE penetration levels without long duration storage if they have available firm RE resources (e.g., dispatchable hydro, biomass, geothermal, etc.). However, riding through inevitable multi-day events of low energy production by VRE resources requires a tremendous amount of energy storage in the absence of firm generation. As a consequence, the amount of BESS needed in a system and its associated costs increase exponentially as VRE penetration approaches 100%.

<u>Project Status/Results</u>: To assess policy-related, technical, and commercial aspects of BESS development in the PICs under this project, HNEI partnered with contractor Delphos International, undertaking three Tasks: 1) reviewing regional BESS policy frameworks and technical guidelines; 2) developing technical and commercial assessments for the private sector's participation in BESS under public-private partnerships (PPPs) and auction arrangements; and 3) designing PICs' BESS development roadmaps.

As part of Tasks 1 and 2, staff from HNEI's Grid*START* developed a spreadsheet-based model to evaluate alternative VRE resources build-outs (solar and wind) for each PIC and associated BESS capacity and energy needs to meet increasing RE targets without excessive curtailment of RE produced. In Task 3, HNEI developed a roadmap for the deployment of BESS in three specific countries (FSM, RMI and Tuvalu) and evaluated how the electrification of transportation in each country may impact the BESS and VRE needs assessed in Tasks 1 and 2. The report for Task 3 is pending submission by Delphos to the World Bank.

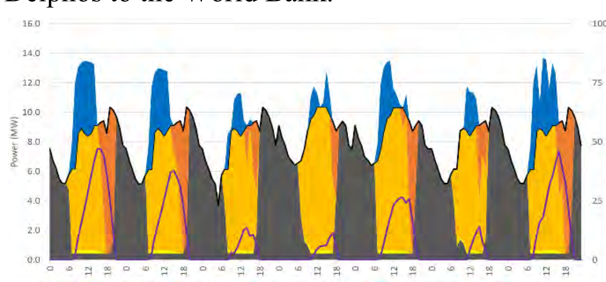

Figure 2. BESS dispatch as a function of VRE generation.

Funding Source: World Bank

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Last Updated: November 2022

H9: Support to the USAID Energy Secure Philippines (ESP) Program

OBJECTIVE AND SIGNIFICANCE: HNEI via its Grid System Technologies Advanced Research Team (Grid*START*) is supporting the USAID-funded Energy Secure Philippines (ESP) Program and Philippines Energy Regulatory Commission's (ERC) activities to advance inclusive economic growth and resilient energy sector development through the enactment of net energy metering (NEM) rules for their numerous small island grid systems and a regulatory framework for battery energy storage systems (BESS) adoption in the Philippines.

Figure 1. Palawan Island, Philippines.

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

In 2020, PDOE issued a new Net Metering Policy which, while maintaining the 100 kW limit on system capacity, removed the Distribution Impact Study fee imposed by distribution utilities on Net-Metering applicants. As a result, the participation rate in the Net-Metering Program has increased by almost 15%. HNEI is continuing its support of the Philippines power sector in collaboration with the USAID ESP program. The three major objectives of ESP are to: 1) improve electric utility performance; 2) increase deployment of advanced energy sources and systems; and 3) enhance competition in the power sector.

PROJECT STATUS/RESULTS:

NEM Rules for Island Systems: HNEI is collaborating with USAID ESP, the ERC, distribution utilities (DUs), and other relevant agencies to develop a set of rules (including guiding principles, processes, rules, and enrollment, and interconnection standards) for a NEM program that allows customers to sell excess distributed generation to the DUs of small island systems not connected to the country's bulk transmission networks.

BESS Regulatory Framework: HNEI is collaborating with USAID ESP and the ERC to establish a mandated BESS regulatory framework for the Philippines, including: 1) streamlined rules for BESS interconnection; 2) guidelines for BESS technical codes and standards; 3) cost recovery mechanisms for utility-owned BESS; and 4) third-party-owned BESS for ancillary services. This work will assist the ERC in fulfilling the mandate set by the PDOE.

In the summer of 2022, HNEI submitted to USAID ESP and the ERC its reports and supporting documentation for: 1) NEM rules for isolated "off-grid" island systems in the Philippines; and 2) a BESS regulatory framework for the Philippines. HNEI conducted in-person presentations of the reports to ESP and the ERC over the course of two full-day sessions held in Manila in August 2022. In September 2022, as a follow-on to the presentation of the BESS report, HNEI led a regulation drafting workshop with the ESP and the ERC in Manila to prepare a draft BESS regulation for ERC promulgation. Work on a draft regulation for off-grid NEM is expected to continue into 2023.

Figure 2. HNEI August 2022 Presentation of BESS Report to USAID ESP and the ERC in Manila.

Funding Source: USAID ESP Program; Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

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Hawaiʻi Natural Energy Institute Research Highlights

Appendix H: International

H10: USAID Sustainable Energy for Indonesia's Advancing Resilience (SINAR) Project

OBJECTIVE AND SIGNIFICANCE: In September 2021, HNEI was contracted by Tetra Tech ES to support USAID's Sustainable Energy for Indonesia's Advancing Resilience (SINAR) program, which seeks to advance Indonesia's development goals in expanding reliable and equitable energy services necessary for sustainable development and inclusive economic growth. The objectives of the SINAR program 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. To help the SINAR program achieve its objectives, staff from HNEI's Grid System Technologies Advanced Research Team (Grid*START*) is providing technical support.

Figure 1. Downtown Jakarta, Indonesia.

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: Grid*START*'s tasks for supporting USAID SINAR involve capacity building on topics including:

- financing for advanced energy systems;
- enabling an environment for deployment and investment in advanced energy systems;
- improving utility cost recovery mechanisms;
- modernizing utility planning and operating practices;
- incorporating competitive procurement standards into energy planning;
- increasing the capacity of Indonesian institutions to use domestic resources;
- improving coordination among relevant stakeholders; and
- enhancing energy sector policies, regulations and standards.

In February 2022, 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.

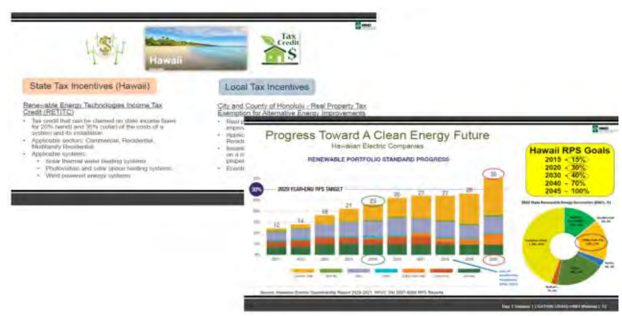

Figure 2. Sample Slides from the February 2022 Webinar.

Follow-on webinars/in-person presentations on topics potentially including: the energy transition process, resiliency measures to address climate change, interagency partnerships in the renewable energy sector, and renewable energy procurement processes, are being explored for 2023 with Indonesia's MEMR and PLN.

Funding Source: USAID SINAR Program; Office of Naval Research

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