UNIVERSITY of HAWAIʻI®
Ke Kulanui o Hawaiʻi

David Lassner
President

DEPT. COMM. NO. 123

December 13, 2024

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

The Honorable Nadine K. Nakamura, Speaker
and Members of the House of Representatives
Thirty-Third State Legislature
Honolulu, Hawaiʻi 96813

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

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

In accordance with Section 93-16, Hawaiʻi Revised Statutes, this report may be viewed electronically at: https://www.hawaii.edu/govrel/docs/reports/2025/hrs304a-1891_2025_hnei_annual-report.pdf.

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

Sincerely,

David Lassner
President

Enclosure

2444 Dole Street, Bachman Hall
Honolulu, Hawaiʻi 96822
Telephone: (808) 956-8207
Fax: (808) 956-5286

UNIVERSITY OF HAWAIʻI SYSTEM ANNUAL REPORT

REPORT TO THE 2025 LEGISLATURE

Annual Report from the
Hawaiʻi Natural Energy Institute

HRS 304A-1891

December 2024

Hawaiʻi Natural Energy Institute

School of Ocean and Earth Science and Technology

University of Hawaiʻi at Mānoa

Annual Report to the 2025 Legislature

HRS 304A-1891

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

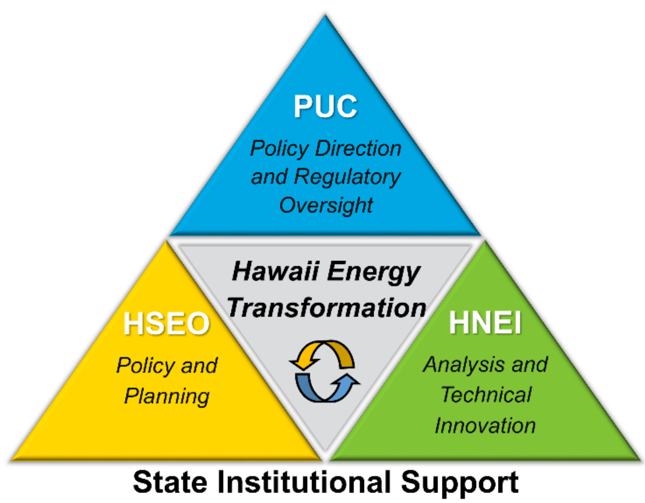
1. INTRODUCTION

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

In 2007, the Hawaiʻi Legislature (Act 253) established HNEI in state law with an expanded mandate to coordinate with state and federal agencies to demonstrate and deploy renewable energy, energy efficiency, and peak demand reduction technologies. Act 253 (2007) also established the Energy Systems Development Special Fund (ESDSF) and directed that it be managed by HNEI. Three years later, in 2010, Act 73 authorized 10 cents of the $1.05 tax imposed on each barrel of petroleum product imported into Hawaiʻi be deposited into the ESDSF. These funds are intended to match funds from federal and private sources, and to award contracts or grants for developing and deploying renewable energy technologies (HRS Secs. 304A-1891-1894 and Sec. 304A-2169.1). In 2022, $0.03 (3 cents) per barrel of the ESDSF allocation was redirected to the Hawaiʻi Public Utilities Commission (PUC) to support the development of EV infrastructure.

Hawaiʻi's energy transformation has been driven by bold state policies that now include a mandate for 100% renewable electricity and carbon neutrality by 2045 (HRS Secs. 269-92 & 225P-5). A core part of HNEI's mission, going beyond traditional academic research, is to support Hawaiʻi in its clean energy transformation by helping facilitate cost effective and practical solutions to deliver renewable energy for the state and its citizens. As part of this effort, HNEI robustly supports analysis to inform energy policy and decision making in Hawaiʻi. The analysis conducted by HNEI and its contractors is used by the utility and PUC in their decision making. HNEI also serves as a critical bridge to Federal initiatives in supporting the State's 100% renewable portfolio standard and clean transportation initiatives. HNEI is recognized as an independent organization providing trustworthy and practical information to support safe, reliable economic development of renewable energy systems and technologies.

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



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

2. HAWAIʻI NATURAL ENERGY INSTITUTE STAFFING/FUNDING OVERVIEW

As an Organized Research Unit in the School of Ocean and Earth Science and Technology at the University of Hawaiʻi at Mānoa (UH), HNEI receives state funding via the Hawaiʻi General Fund through the university budget, sufficient to support its Director, up to three administrative support staff, and partial salaries (60% to 80%) of six tenure or tenure-track faculty (permanent faculty). HNEI has received approval to hire two additional tenure track faculty expected to help support the state's decarbonization goals, and HNEI is currently in the process of filling one of these positions. HNEI staffing for 2024 is summarized in Table 1 below.

Table 1. HNEI total staffing by position type for 2024.

Director: Richard E. Rocheleau	
Permanent Faculty (FTE)	6
Other Permanent Staff (APT)	3
Temporary Faculty	18
Other Temporary Staff [(a)] (APT, RCUH)	25
Training [(b)]	17

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

As summarized in Table 2, HNEI's primary source of funding is from extramural awards from various federal agencies. In recent years, the majority of these funds have been from the Office of Naval Research, the U.S. Department of Energy, and Naval Facilities Engineering Command, but HNEI also receives funds from other U.S. Federal agencies and industry as well. A complete breakdown of HNEI awards for FY 2022 through FY 2024 is shown in Tables 3 through 5.

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

HNEI also receives a small amount of tuition return. HNEI's extramural awards also generate indirect "Research and Training Revolving Funds," of which approximately 25% is returned to HNEI to facilitate operations and research. In addition to addressing national and international needs, many of the projects funded by the entities identified directly or indirectly support Hawaiʻi's clean energy goals.

As part of its responsibilities under Act 253, HNEI also administers the Energy Systems Development Special Fund (ESDSF), allocated from the environmental response, energy, and food security tax ("Barrel Tax") pursuant to HRS Section 243-3.5. Funding from the ESDSF serves as an invaluable source of funding for HNEI. The primary uses of the ESDSF over the last three years were to: 1) provide cost share to federally funded energy research when non-federal cost share is required to secure the funds; 2) provide funds to address explicit PUC and legislative requests, including unfunded legislative mandates; and 3) to support select community engagement efforts, such as the annual Hawai‘i Energy Conference and the Hawai‘i Energy Policy Forum, whose activities include the annual legislative energy briefing. Every three years, HNEI prepares a report summarizing ESDSF projects and expenditures. The last such report was submitted to the legislature in December 2023.

While HNEI does not typically initiate legislation the Institute actively engages in activities to inform legislators and other Hawai‘i government organizations with unbiased information and analysis on matters relevant to pending issues, bills, and proposals. Many of these activities are summarized in Appendices A and B. For example, HNEI continues to provide support to the PUC, including detailed analytic studies for evaluation of utility proposals. HNEI is also a founding 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. In collaboration with the Forum, the Institute is currently preparing a series of briefs for the pending legislative session.

A breakdown of HNEI funding by type for the past three fiscal years is shown in Table 2 on the following page.

Table 2. Funding by source and year, FY 2022 to FY 2024.

	FY 2022	FY 2023	FY 2024
General Funds	$1,329,727	$1,259,349	$1,182,434
Tuition and Fees S Funds	$49,897	$32,870	$28,684
Extramural Awards	$15,205,393	$5,543,660	$18,714,930
Research and Training Revolving*	$351,258	$446,794	$539,496

**RTRF funds are based on the previous year's expenditures.*
Note: In FY 2025, HNEI has received $9,422,615 in extramural awards to date.

Table 3. Summary of HNEI Extramural Funding, FY 2022.

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

Table 4. Summary of HNEI Extramural Funding, FY 2023.

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

Table 5. Summary of HNEI Extramural Funding, FY 2024.

Office of Naval Research, Sustainable Energy Systems	$10,999,994
Office of Naval Research, Fuel Cells	$150,000
FAA, Sustainable Aviation Fuels	$250,000
U.S. Dept. of Energy, Fuel Cells	$4,000,000
U.S. Dept. of Energy, Microgrid Training	$999,838
U.S. Dept. of Energy, Grid Technology via UAF	$97,769
U.S. Dept. of Energy, Semi-Monolithic Devices for Hydrogen	$1,000,000
U.S. Dept. of Energy, 2D Materials for Solar Films	$250,000
U.S. Dept. of Energy, Wave Energy via NREL	$183,500
National Science Foundation, Materials Research	$21,563
U.S. Dept. of Agriculture, Hawai‘i Climate Smart Commodities	$60,805
SINTEF (Norway), Biocarbons	$48,795
Deloitte & Touche, International	$145,664
DAI Global, International	$227,778
Element Energy, Battery Testing	$200,178
USAID, International via Tetra Tech	$79,046
FY 2024 Total	**$18,714,930**

3. RESEARCH SUMMARIES

Extramural funds garnered by HNEI support programs across a broad range of technologies and end uses. Areas of activity in 2024 included: Hawai‘i Energy Analysis – Community Support; Hawai‘i Energy Systems – Future Energy Systems; Grid Technology Development; Alternative Fuels including sustainable aviation, biofuels, and hydrogen; Electrochemical Power Systems including fuel cells and battery technology; Advanced Materials, Ocean Energy, and an active and growing International presence.

In 2024, HNEI conducted or provided leadership for 52 discrete projects. Of these 52 projects, approximately 25% are funded or co-funded by the ESDSF. The various activities and key accomplishments under each of these projects are documented in the summaries contained within the eight 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 eight Appendices and a full listing of their corresponding page numbers follows.

Appendix A: Hawai‘i Energy Analysis – Community Support

HNEI and its contractors conduct analysis across a broad range of issues. These may result from legislation, but are often selected based on informal requests based on discussions with legislators or state agencies, such as the Hawai‘i State Energy Office or the Hawai‘i Public Utility Commission (PUC). They may also arise from interactions with the utility, but only where they address state or PUC interests. During this reporting period, the work relied heavily on models and data developed by HNEI and its primary consulting partner, Telos Energy. The focus of the efforts in this section tend to be analyses related to more immediate problems facing Hawai‘i's electricity grids and policy makers. The work described in Appendices A1 and A2 reflects support to the Hawai‘i Public Utilities Commission. Appendix A3 is a short summary of HNEI activities to reinvigorate the Hawai‘i Energy Policy Forum. With a re-envisioning of how to engage a broad array of stakeholders, this is expected to be a major activity in the upcoming year. Appendix A4 summarizes a small effort supporting NELHA's planning efforts in the energy area. Appendix A5 describes ongoing work initiated with a legislative request to evaluate the disposal and recycling of clean energy products in Hawai‘i. This topic has garnered broad interest across the state and, in 2025, will be integrated into the Policy Forum activities.

Appendix B: Hawai‘i Energy Systems –Future Energy Systems

As part of its work to support the state's progress to achieve very high penetration of renewable energy, HNEI and its contractors continue to assess the impact of the transition to variable renewable generation on the reliability of the islands' grids. While the integration of battery energy storage is enabling reliable grids (resource adequacy), as we transition to high use of variable renewable sources, these studies also provide clear evidence that the need for significant amounts of firm-dispatchable generation will remain. With the aging generation fleet in the Hawaiian Electric system, there will be a need for investment in this area. Appendices B1 and B2 summarize grid reliability issues under conditions of high variable generation and summarizes firm power needs during this transition. Appendix B3 discusses in more detail some of the recent grid reliability events on O‘ahu, while B4 and B5 explore future options for addressing cost and reliability during the transition.

Appendix C: Grid Technology Development

With its high penetration of distributed rooftop solar and the pending utility scale solar + storage projects, Hawai‘i is at the forefront of tackling the problem of renewable energy integration. The geographic isolation of the islands' electricity grids and the rapid growth of renewable generation can make Hawai‘i's electricity grids 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 Hawai‘i leveraged with funding from the ESDSF.

Appendices C1 through C8 summarize eight grid or microgrid relevant technology development efforts. These include: development and demonstration of a high efficiency DC microgrid at Coconut Island (C1); demonstration of advanced conservation voltage reduction technology demonstrated at the Marine Corps Base on Okinawa (B2); continued development and demonstration of a virtual power plant on Maui (B3); a project to further understanding of the dynamic response of inverter dominated power systems (B4); development and deployment of a bidirectional EV charging system on the UH campus for optimized ride sharing (B5); planning for EV charging infrastructure for USMC Camp Fuji in Japan (B6); development of new methodologies to estimate PV hosting capacity (B7); and development of tools for microgrid design (B8).

Appendix D: Alternative Fuels

Alternative fuels are an important component of Hawaiʻi's efforts to reduce its dependence on imported petroleum and an essential piece for reducing Hawaiʻi's greenhouse gas footprint. Within this topical area, HNEI conducts research, testing, and evaluation that seeks to support the potential for alternative fuels production in Hawaiʻi. HNEI projects one focused on sustainable aviation fuels (Appendix D1) and one focused on enhanced fuels characterization methodologies (Appendix D2). HNEI is also actively researching the production of novel biocarbon materials using a slow pyrolysis process (Appendix D3), and novel processes for production of solar fuels with primary emphasis on photoelectrochemical hydrogen production (Appendix D4). Appendix D5 provides an update to HNEI's efforts to provide technical support and fuel (hydrogen) for several electric-fuel cell hybrid buses to be operated by the Hawaiʻi Island Mass Transit Agency (Hele-on bus).

Appendix E: Electrochemical Power Systems

HNEI has been conducting state-of-the-art research, development, and testing of fuel cell and battery technologies for over two decades. The primary objective 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 E summarizes the ten distinct projects HNEI conducts in this area. Appendix E1 summarizes HNEI's ongoing partnership with the Naval Research Laboratory to develop reliable fuel cell power systems for unmanned aerial vehicles. Appendices E2 through E7 describe different efforts for development of more efficient, lower-cost fuel cells, including both proton-exchange and anion-exchange membrane technologies. Finally, Appendices E8 through E10 describe three projects intended to inform the use of Li-ion energy storage systems. More detailed descriptions of each of these efforts are found in Appendix E.

Appendix F: Advanced Materials

The four projects included in the Advanced Materials group, include three projects focused on the development of novel techniques for the production of thin-film materials for electronic and solar application low cost photovoltaics (Appendices F1 through F3); and one project to design and develop novel filtration materials in support of HNEI's fuel cell development (F4).

Appendix G: Ocean Energy

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 since 2015. The Navy Wave Energy Test Site (WETS) located offshore from

Marine Corps Base Hawai‘i is a premier open water test site in the U.S. Appendix G1 summarizes HNEI's support and recent and planned activities at the site. Appendix G2 provides an update of work funded by the U.S. Department of Energy supporting HNEI's efforts to develop its own wave energy technology.

Appendix H: International Support

In 2017, HNEI was the recipient of a multimillion-dollar award from the Office of Naval Research (ONR) titled "Asia-Pacific Regional Energy Systems Assessment (APRESA)," intended to facilitate development of clean, resilient, and efficient energy systems throughout the Asia-Pacific region. HNEI has leveraged this initial ONR funded effort to develop a wide range of partnership and new funding sources derived from USAID and World Bank programs. Appendix 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 and H3 provide additional detail for two of the many projects initiated under APRESA. Appendices H4 through H13 summarizes the recent work supported by USAID and the World Bank (via subcontracts to the prime) that took place across the Asia-Pacific region, including in Papua New Guinea, the Philippines, and Indonesia; and a new effort in the Caribbean region.

APPENDICES

Appendix A: Hawai‘i Energy Analysis – Community Support

Appendix B: Hawai‘i Energy Systems – Future Energy Systems

Appendix C: Grid Technology Development

Appendix D: Alternative Fuels

Appendix E: Electrochemical Power Systems

Appendix F: Advanced Materials

Appendix G: Ocean Energy

Appendix H: International

A1: Decision Support Services to the Hawaiʻi Public Utility Commission

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

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

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

Examples of recent support included a review of HECO's distributed energy resources (DER) rate design and grid service definitions [Docket #2019-0323], competitive solicitations in the Stage 1, 2, and Stage 3 utility energy procurements [Docket #2017-0352], ongoing reliability concerns on Oʻahu and Maui [Docket #2021-0024], and the GHG Waiver of for renewable energy and storage systems [Docket #2024-0217].

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

- Oʻahu reliability post AES retirement;
- Maui oil unit retirement and replacement;
- Firm renewable needs; and
- Time of use rates and DER rate design.

PROJECT STATUS/RESULTS: The HNEI-Telos team met with the Commission in person in March 2024 to discuss ongoing developments at the utility, HNEI analysis, and other critical issues for the state.

Clean Firm Resource Needs In Hawaiʻi (Appendix B2): HNEI conducted a study to inform ongoing procurement and proposed legislation for both variable and firm renewable energy. It sought to determine the minimum amount of firm power that the system would require at various levels of wind, solar, and storage additions. It also informed decisions on whether to integrate more variable renewable energy today, considering that these decisions may shut the door on future options. This information can be used to determine characteristics of future systems to inform decisions on oil-fired power plant retirements, procurement of new resources, and to show how robust the system can be with variable renewable energy and storage alone.

In the past year, HNEI expanded that analysis to consider specific resources that could provide the firm renewable needs, including biodiesel, hydrogen, and multi-day energy storage and conducted a detailed assessment on the flexibility needs, if any, of new firm resources. This included a detailed representation of ramp rates and cycling capability, including the impact of solar and load forecast errors on utility operations.

At the end of 2023, HECO announced the final award group of the Stage 3 RFP [Docket #2017-0352], which included 700 MW of firm resources, including a contractual extension of the 208 MW Kalaeloa combined cycle plant and 60 MW Hāmākua plant, a HECO self-build proposal to repower the Waiau plant with 253 MW of new gas turbines, and 175 MW of additional reciprocating engines or gas turbines across Oʻahu and Maui. These proposals are currently under contract negotiations with HECO and expected to be filed with the Public Utilities Commission in early 2025.

As specific projects are considered, HNEI will review proposals and provide recommendations and analysis to the Commission upon request.

Recent Reliability Challenges (Appendix B3): 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, 2022, 2023, and 2024, the HNEI-Telos Energy team routinely conducted reliability analysis of the retirement to brief HECO, the PUC, and the Governor's Power Past Coal Task Force on the impacts of project delays, cancellations, and other events [Docket #2021-0024].

At the beginning of 2024 the Kapolei Energy Storage (KES) plant became operational, largely replacing the AES coal plant retirement. In addition, three of the four Stage 1 solar + storage projects started operating in the second half of 2023 or throughout 2024. While these additions helped improve the reliability situation on Oʻahu, continued forced outages and reliability concerns of the steam oil fleet persisted throughout the year. As a result, grid reliability on Oʻahu continued to be challenged throughout 2024.

Throughout 2024, HNEI regularly reviewed operational data from new systems, tracked outage rates on existing oil-fired capacity, and conducted post-mortems on grid reliability 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 in 2022, are being used to assess capacity reliability risks associated with the new resource mix on Oʻahu, including updates for utility plans, impacts due to delays in project schedules, new trends in HECO's generator outage rates, and changes to system load. Analysis shows that while there was a resource adequacy shortfall in January 2024, this largely stemmed from outages at the Waiau power plant and did not result from the recent transition to solar and storage resources. In addition, another review of grid operations in July 2024 showed that new solar and battery storage resources were instrumental in maintaining grid reliability after three of the largest oil-fired power plants went on outage simultaneously.

Maui Oil Unit Retirement and Replacement: The Kahului Power Plant (KPP) was originally scheduled to retire by the end of 2024, but this date was extended to the end of 2027 due to reliability concerns on Maui. Analysis from 2021-2023 showed how the retirement could be reliably achieved with proposed solar + storage projects. Since that analysis, project delays have occurred with replacement resources. In addition, the Māʻalaea M10-M13 diesel engine may need to be retired earlier than expected. The combined retirements would represent the loss of over 85 MW of firm capacity, over 40% of Maui's peak demand.

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

The HNEI-Telos team continues to monitor ongoing developments in Maui, including the status of Stage 1 and Stage 2 project commissioning and cancellations, adoption of DER and BTM storage, peak load levels, and generator reliability. While the M10-13 plants are expected to remain available until sometime between 2027-2029, any new capacity additions beyond those under development in Stage 1 and 2 will likely take significant time to develop. As a result, HNEI will continue to support the Commission with independent reviews of Maui reliability.

Analysis of TOU Rates and Load Flexibility (Appendix B5): In 2024, there were two notable developments at the Commission. The first was the initial voluntary implementation of HECO's new time of use (TOU) rates and new DER tariffs for exported generation [Docket #2019-0323]. To support the Commission in their review of these priorities, the HNEI-Telos team conducted a TOU Rate analysis.

This work continued the review of HECO's AMI data to calculate changes to bill payments with and without the new TOU structure, but extended the analysis to evaluate the potential grid benefits of shifted load profiles. This included potential energy savings and reduced oil consumption, as well as deferred capacity savings through reduced on-peak consumption. Results of this analysis showed that while TOU rates can shift generation to periods when solar is more available, recent additions of battery energy storage saturated the benefits that this type of load shifting could provide.

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

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2024

OBJECTIVE AND SIGNIFICANCE: In 2018, under guidance from the Hawaiʻi Public Utilities Commission (PUC), the Hawaiian Electric Company (HECO) initiated the Integrated Grid Planning (IGP) process to determine the types of resources and grid services the utility should invest in over the coming years to meet the goals of legislatively mandated Renewable Portfolio Standards. A Technical Advisory Panel (TAP) was established to provide a third-party, technical, and unbiased review of HECO's modeling and analysis efforts to ensure that the best tools and methodologies are being used. The TAP consists of experts from around the country including members from National Laboratories, industry groups and other utilities. Based on direction from PUC Order No. 36725, *Providing Guidance on the IGP*, HNEI chaired the IGP's TAP from its inception in 2018 to October 2021 and continued to stay engaged in the TAP throughout 2022-2024.

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

Key activities of the TAP have focused on assisting HECO in revising their approaches to analysis. These have included advice regarding 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. HECO also adopted probabilistic modeling methods developed first implemented by HNEI to quantify the resource adequacy of future proposed systems and leveraged HNEI's experience when reviewing the proposed energy reserve margins and associated reliability metrics.

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

Throughout 2020-2023, HECO continued to develop its IGP, working in consultation with stakeholder groups and the TAP. Throughout that period, HNEI continued to play a very active role in all aspects of the IGP process and TAP, providing regular

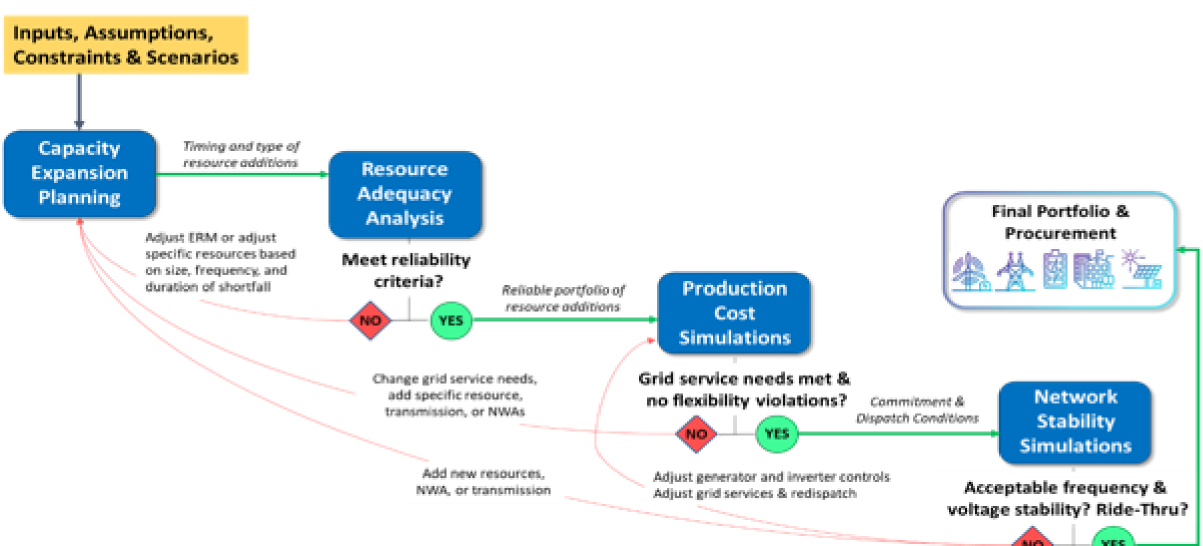


Figure 1. HNEI modeling framework adopted by the IGP.

suggestions, independent modeling assessments, and written comments in the PUC docket.

At the end of 2023, the final IGP was submitted by HECO, with an annual update filed in 2024. During 2024, the Public Utilities Commission made final orders on the IGP filing, as well as proposed actions for future IGP planning cycles.

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

In 2022, HNEI and its contractor, Telos Energy, raised numerous concerns and corrective recommendations about the excessive use of the capacity expansion model, RESOLVE, in evaluating impacts and implications related to its use in characterizing reliability and grid service needs. HNEI has demonstrated that these types of analyses should be done in tandem with probabilistic analyses that can be used to measure grid reliability from the use of RESOLVE.

As a result of these recommendations, HECO adopted HNEI's probabilistic analysis framework at the end of 2022 and throughout 2024. Now included in all the IGP filings as well as HECO's RFP is a probabilistic framework that quantifies the loss of load probability across different future resource mix years and procurement cycles. It considers the impact of forced outages, load variability, and weather impacts on solar and wind resources.

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

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

In 2024, the PUC reviewed the final IGP and provided recommendations for updates and future implementation. This required HECO to submit preferred plans for future development and proposals for future IGP cycles. The HNEI team continued to review PUC orders and updated plans submitted by HECO. In addition, the TAP was requested to convene in 2024 on specific topics associated primarily with solar and battery interconnection and resource adequacy modeling needs.

In parallel, HECO is starting the resource procurement process to add new resources to meet the near-term proposals outlined in the IGP. To do this, HECO is continuing its competitive solicitation process via the Stage 3 RFP. HNEI and Telos Energy have provided both the Commission and HECO feedback on this RFP and are awaiting notification of the selected projects. At that time, the HNEI-Telos team will review proposed projects and may conduct independent reviews of modeling and analysis.

As the IGP continues into future planning cycles, the HNEI team will continue to provide technical and unbiased review for HECO's long-term planning and procurement process to ensure that the State can achieve its ambitious renewable energy goals 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 2024

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 (CSS) Public Policies Center (PPC) as a collaborative energy planning and policy group consisting of Hawaiʻi's electric utilities, oil and synthetic natural gas suppliers, environmental and community groups, renewable energy industry, academia, and federal, state, and local government. In its first five years, the Forum was instrumental in promoting funding and needed reform for the State's utility regulatory agencies (i.e., the Public Utilities Commission (PUC) and the Division of Consumer Advocacy), and commissioned studies, reports, and briefings to raise the level of dialog concerning energy issues for legislators and the general public.

In past years, the Forum has sponsored and organized Legislative Briefings at the Capitol at the opening of each legislative session, an annual Hawaiʻi Clean Energy Day event, and sponsors programs to develop reliable information and educate and raise awareness in the community.

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, outreach, and public education.

PROJECT STATUS/RESULTS: Following the departure of HNEI faculty who managed the Hawaiʻi Energy Policy Forum (HEPF) activities through the 2023 legislative briefing, HEPF activities were temporarily paused. However, with the hiring of new faculty, these activities have resumed.

In the third quarter of 2024, the HEPF Steering Committee, consisting of over 23 members, convened to identify priority topics for the Forum. The Steering Committee includes representatives from electric utilities, oil and natural gas suppliers, environmental and community groups, the renewable energy sector, academia, and various levels of government. This group plays a crucial role in setting the Forum's research and policy priorities for the coming year and will meet monthly to prioritize key research topics for HNEI faculty to focus on. Their input will support independent, unbiased research to help policymakers and industry leaders address critical issues facing our state.

In 2024, the HEPF took the following actions:

- Relaunched and reconvened the HEPF, focusing on increasing membership, reorganization, and new objectives for the Forum;
- Created a Steering Committee comprised of over 23 members from industry, state and local government, environmental groups, developers, academia, and utilities to direct HEPF activities for the coming year; and
- Developed a list of research topics and priorities for the upcoming year that the Steering Committee is currently vetting.

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

Funding Source: Energy Systems Development Special Fund

Contact: Richard Rocheleau, rochelea@hawaii.edu; Jennifer Potter, jmpotter@hawaii.edu

Last Updated: November 2024

A4: NELHA Energy Plan

Objective and Significance: This project supports Natural Energy Laboratory of Hawaiʻi Authority (NELHA)'s development of an updated energy program that will support the state's energy goals. The previous energy plan focused on how NELHA could use in-house resources to obtain funding for demonstrations of distributed energy resources. Based on the recent legislative request, this set of recommendations is more broadly focused on what additional resources will be needed to allow NELHA to be more effective in supporting the state's energy goals.

Background: The enabling legislation creating NELHA is contained in Section 227D-2 which provides for the "Establishment of the natural energy laboratory of Hawaiʻi authority". "The purpose of the natural energy laboratory of Hawaiʻi authority shall be to facilitate research, development, and commercialization of natural energy resources and ocean-related research, technology, and industry in Hawaiʻi and to engage in retail, commercial, or tourism activities that will financially support that research, development, and commercialization at a research and technology park in Hawaiʻi." Based on this legislation, NELHA leadership was asked by the legislature to determine how NELHA could best support the state's energy goals. As a result, NELHA requested HNEI's support in determining paths forward in responding to this question.

Project Status/Results: The nature of the legislative request required an evaluation of current NELHA capabilities. Effectively, NELHA is a landlord for tenant companies with its chief contribution being a utility provider, specifically ocean water, including water pumped from below the thermocline. As a result, NELHA has considerably more capabilities in ocean sciences as compared to energy systems.

HNEI has developed draft recommendations to NELHA as to how it can best respond to the legislative request. Development of the draft entailed interviews with various stakeholders and NELHA board members to better incorporate a range of possible energy initiatives. A range of suggestions were made by the interviewees. In particular, a number of them raised the idea of NELHA obtaining Department of Land and Natural Resources land to find mechanisms to spur the growth of geothermal energy on the Big Island.

The draft has been reviewed and commented upon by NELHA leadership. As a result, a draft presentation has been presented to the NELHA board to obtain their comments and critique. Specific early commentary by the Board was to discuss in greater detail the potential for utilizing state lands under NELHA for further development. An additional set of comments discussed the need for NELHA to find mechanisms for improved outreach to local communities in order to include them in some new projects. Based on these comments, additional meetings will be held to expand on these ideas.

Following these meetings, a revised draft set of recommendations will be submitted to NELHA management. The current plan is to receive comments from NELHA management and make appropriate revisions to the recommendations. HNEI anticipates that the final set of recommendations will be submitted to NELHA leadership by the end of the year.

Funding Source: Energy Systems Development Special Fund

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2024

A5: Disposal and Recycling of Clean Energy Products in Hawaiʻi

OBJECTIVE AND SIGNIFICANCE: Hawaiʻi's pursuit to become fully renewable by 2045 will produce substantial streams of clean energy product waste over the next 30 years and beyond. In recent years, Hawaiʻi has seen a large uptake in the use of solar photovoltaic (PV) panels. This is expected to continue with new systems, both rooftop and utility scale, combined with battery energy storage systems. Due to this, it is crucial for the state to develop a process to manage these waste streams in a manner that is both safe and environmentally sound. The objective of this work is twofold: 1) to quantify this waste stream and enumerate best practices for cost-effective recycling and 2) to recommend best practices for disposal, recycling, or secondary use of clean energy products produced in the State.

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

PROJECT STATUS/RESULTS: This project, commenced in September 2021, remains ongoing. Findings to date include: 1) material composition of PV panels, inverters, cabling, mounting equipment and Li-ion battery storage as a function of installed power (kg/kW); 2) cumulative PV and battery storage installed by island for residential, commercial, and utility scale since 2005; 3) projected disposal loading rate of aging PV materials to 2045; 4) assessment of waste treatment options, costs, and risks; and 5) assessment of fee options with recommendations. Specifics:

1. As of 2021, it is estimated that 3.86 million modules have been installed on Oʻahu, 720,000 in Maui County, 580,000 in Hawaiʻi County, and 480,000 on Kauaʻi; representing up to 225,000 tons of PV related clean energy materials. For comparison, 2,570,478 tons of municipal solid and commercial/demolition waste generated in the State during the 2021 calendar years. The total amount of these PV related clean energy materials installed to date is equivalent to approximately 8.8% of the total municipal solid and commercial and demolition waste generated in a single year (2021).
2. Covering the cost of off-island disposal for PV panels and Li-ion batteries is likely to require one or more revenue-generating schemes, potentially including waste generator or producer responsibility, state encouraged/ assisted recycle, and/or visible fees.
3. The possibility of enhanced restrictions or outright banning of ocean shipping of end-of-life Li-ion batteries is identified as an existential threat to Hawaiʻi's disposal of Li-ion batteries.
4. The need to deactivate and/or pre-process Li-ion batteries on island was identified as needed to ensure long term access to ocean transport.

These and other results have been detailed in HNEI's report "***Recommendations on Waste Management of Clean Energy Products in Hawaiʻi***," which was previously submitted to the legislature. Although not mandated, this work was continued in 2022 and 2023 to add depth to policy recommendations for the disposal and recycling of clean energy materials in Hawaiʻi and a **supplemental report(s)** was produced and is available on HNEI's website.

FUTURE WORK: To support state decision making in regard to the potential needs for development of a Li-ion battery deactivation and/or preprocessing facilities in Hawaiʻi, HNEI is now conducting a comprehensive study to identify the requirements and general costs of: 1) a full pre-processing facility, 2) a full de-activation facility, and 3) a ship-only facility. Outcomes will assist the State in policy decision making as well as soliciting bids as necessary.

Funding Source: Energy Systems Development Special Fund

Contact: Michael Cooney, mcooney@hawaii.edu

Last Updated: November 2024

B1: Grid Reliability with High Solar and Storage Deployment

OBJECTIVE AND SIGNIFICANCE: Hawaiʻi's power systems are undergoing significant change, characterized by the replacement of aging coal and oil generation with variable and less predictable solar and storage resources. This ongoing study shows that grid reliability (resource adequacy) as measured by loss-of-load expectation can be maintained equivalent to or better than the current system even with very high penetrations of variable renewable generation with storage. Maintaining this reliability will require back up support of firm generation resources, during times of low solar and/or wind resource.

KEY RESULTS: Hawaiʻi's electric systems can further expand their renewable energy portfolio, incorporating more solar and storage without any loss of reliability (resource adequacy). Maximizing renewable energy utilization while incorporating the availability of firm capacity resources for those times when renewable output is insufficient will reduce fuel use. To ensure grid stability during periods of low renewable generation, the integration of firm power resources will be crucial. These firm resources will require flexible, dispatchable generation, to provide a consistent energy supply during periods of extended low variable resources (see Appendix B2).

BACKGROUND: Over the past decade, Hawaiʻi has experienced rapid growth in solar energy driven by high oil prices, decreasing costs of solar technologies, and a commitment to reducing the use of fossil fuels. The first major phase of solar integration began with the adoption of distributed rooftop systems – encouraged by net energy metering policies that allowed homeowners to offset electricity costs and receive credit for surplus energy produced. This initial program led to a significant increase in rooftop solar across the islands, as early adopters installed systems that contributed to the state's renewable energy goals.

The second phase of solar expansion saw the development of larger-scale utility solar projects, particularly on Oʻahu. Between 2017 to 2020, Oʻahu added 175 MW of utility-scale solar without battery storage, addressing daytime energy needs and further reducing the reliance on oil-fired generation. However, at this point, mid-day solar generation regularly exceeded half of total demand and there was limited ability to integrate additional solar without storage into the grid.

Currently, a third phase is underway, involving hybrid solar and battery storage projects that can both generate electricity during the day and store a significant amount of the energy for later use during late evening or early morning peak demand periods. Through recent competitive procurements, this new generation of hybrid projects is expected to significantly increase the renewable energy share on the grid.

Relative to the size of the Hawaiʻi grids, these hybrid solar and storage systems are being deployed at a scale not yet seen in other parts of the United States or globally. Simultaneously, coal and oil generation plants are being retired from operation. In 2022, the AES coal plant, Oʻahu's largest single source of electricity, was retired and replaced by solar and storage resources. Similarly, forthcoming oil plants at Kahului and Māʻalaea on Maui are slated for retirement and will be replaced primarily by solar and storage resources with some additional firm flexible generation.

Over the past several years, HNEI has conducted resource adequacy studies for both Oʻahu and Maui, calculating the amount of solar and storage capacity that would be needed at various levels of coal and oil retirements. For Oʻahu, the analysis specifically modeled the retirement of the AES coal plant and the commissioning of the KES standalone battery and determined that the current Oʻahu grid, with the AES coal plant retired and the KES standalone battery in operation would be resource-adequate even with only practical buildout of the Stage 1 projects, but continued oil retirements would require large variable generation additions and backup firm generation.

Results of the 54 evaluated scenarios for Oʻahu are provided in the matrix in Figure 1, 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 1. LOLE (days per year) for 2023 evaluated across 54 scenarios.

HNEI and Telos Energy also conducted a resource adequacy analysis to assess the reliability of the Maui system with the Kahului Power Plant (KPP) and Māʻalaea M10-M13 retirement and replacement solely with variable renewable energy and energy storage.

The analysis indicates that with the KPP 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-M13 in isolation (-50 MW), would require more replacement resources, between 40 and 60 MW – again, a near 1-1 replacement. With both oil plants retired (-81.8 MW), between 80 and 100 MW of replacement solar + storage capacity would be required to maintain reliability. This highlights that full deployment of the under-construction hybrid solar + storage resources plus additional resources would be required to meet current system reliability levels if both plants are retired. The results for Maui are shown in Figure 2.

<u>PROJECT STATUS/RESULTS</u>: Since 2020, HNEI has been conducting and regularly updating analysis on the expected reliability of the Hawaiʻi power systems with additional deployment of solar and storage resources. These studies also explore the potential for additional oil plant retirements. In 2024, HNEI continued to assess the reliability of Hawaiʻi's grids as new solar and storage resources were brought online.

The HNEI analysis utilizes detailed power system models and utilizes sequential Monte Carlo probabilistic modeling which incorporates 25 years of chronological solar data, 8 years of chronological wind data, and hundreds of samples of thermal generator outages to forecast the reliability of the

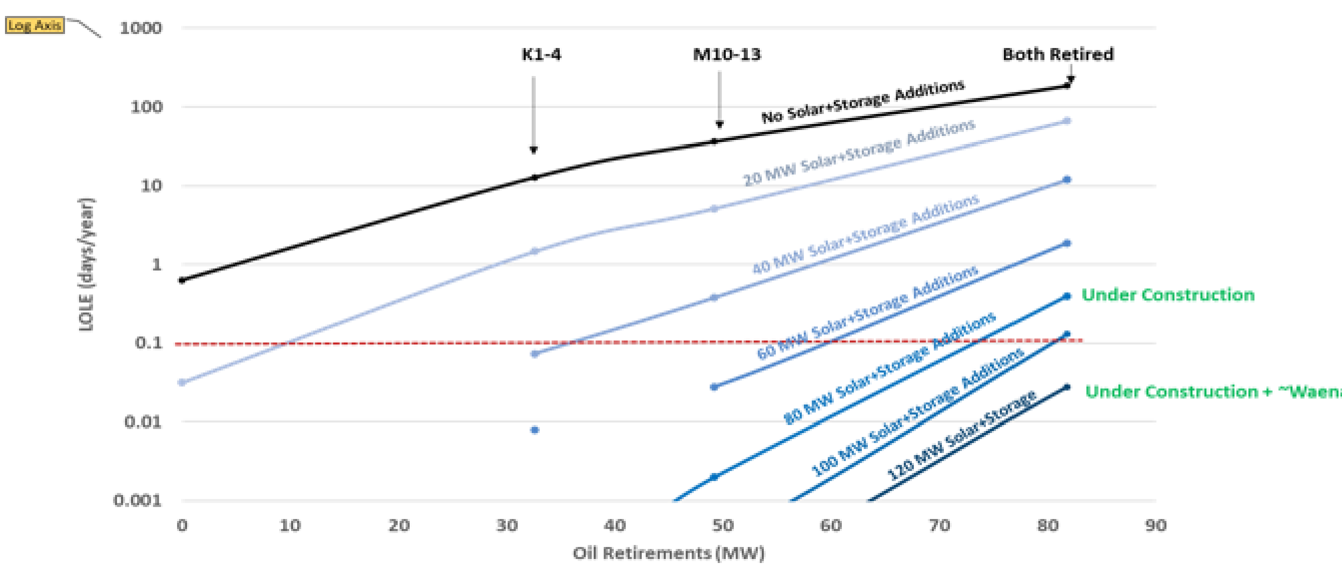


Figure 2. Loss of Load Expectation with oil retirements and solar + storage replacement.

future power system. This process utilized by HNEI was adopted by HECO for grid modeling in 2023.

The analysis suggests that integrating large-scale solar paired with storage can allow Hawai‘i's grids to receive up to 70% or more of their energy needs from variable renewable generation while keeping solar curtailment, the excess energy production that cannot be delivered to the grid, relatively low (Figure 3). Adoption of solar, combined with 4-hour battery storage systems can improve grid reliability when managed effectively with firm resources during periods of low or intermittent variable generation.

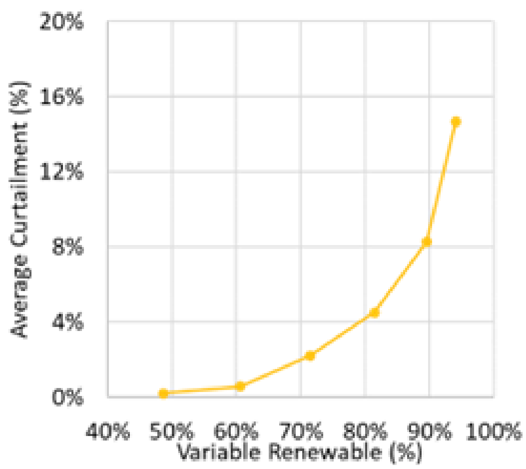


Figure 3. Solar curtailment at increasing shares of variable renewable energy.

Despite these benefits, some stakeholders have expressed concern over intermittent generation resources and the perceived impact on grid reliability. However, HNEI analysis shows that solar and storage resources can continue to be integrated into Hawai‘i's grid at high levels without any loss to resource adequacy when coupled with firm generation resources. The amount of firm capacity required by the system at various levels of solar, storage, and wind and how it would be optimally operated is discussed further in Appendix B2.

Results of this work were presented to the Public Utilities Commission, Hawaiian Electric Company, the Power Past Coal Task Force, and other public forums over the past three years.

HNEI will continue to track the reliability of Hawai‘i’s grids and update this analysis as new solar and storage systems come online, new projects are proposed, and additional retirements are planned.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2024

B2: Clean Firm Resource Needs in Hawaiʻi

Objective and Significance: HNEI is conducting analysis to quantify the need for firm dispatchable generation on Hawaiʻi's grids as the penetration of variable renewables increases. The results of this study help frame the ongoing discussions, debates, and planning related to the role of dispatchable firm capacity. The objective is to inform ongoing procurement and proposed legislation for both variable and firm renewable energy. This study sought to determine the minimum firm capacity required by the system to ensure adequate resource availability at various levels of wind, solar, and storage additions. The findings provide valuable insights into the characteristics needed in future systems. They can inform decisions on oil-fired power plant retirements and guide the procurement of new energy resources.

Key Results: The findings of this analysis indicate that on Oʻahu, even in a very high variable renewable energy and storage grid, there will be a need for firm capacity of 600-750 MW. This number will increase if load increases significantly such as via the adoption of EV. In this future clean energy system, these resources would run more sparingly as the variable generation increases but are necessary for reliability. When the firm resources are in operation, they may need to run at significant levels for several consecutive days, making it difficult, if not impossible, to address reliability issues exclusively relying on battery storage or demand response. Today, this grid service is provided by the existing HECO oil plants. These plants are aging and becoming less reliable. At some point, they will need to be retired and replaced with other forms of firm renewable energy. Given lead times for development of new generation, these decisions need to be considered in the near future.

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

Preliminary results also indicate that flexibility from these resources could be important, especially when uncertainty in solar forecasting is considered. Additional work is being conducted to determine operational considerations for new firm resources and reserve strategies to ensure reliability.

Background: 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 percent of renewable energy be generated by firm renewable energy. These bills also proposed to limit the percentage of any one type of renewable energy source to 45 percent of all generation for each island except for geothermal generated energy. It was unclear if the intent of this requirement was to limit the percentage of distributed PV and utility-scale PV to 45 percent, but since some of the islands already have high levels of these resources, it could have prevented the installation of additional solar systems. These bills were approved by both the Senate and the House but later vetoed by the governor. While these laws are not in statute today, there remain important questions about the need for firm renewable energy and potential solutions to address that need. These are likely to be the topic of future legislative sessions.

On March 1, 2022, Hawaiian Electric Company issued a request for proposals (RFP) seeking to acquire 500 to 700 megawatts of 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."

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.

Project Status/Results: HNEI's analysis of resource adequacy was first conducted for Oʻahu, and the methodology was later extended to the islands of Kauaʻi, Maui, Molokaʻi, Lānaʻi, and Hawaiʻi.

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

The study team evaluated several potential future resource mixes with differing amounts of solar, storage, and wind with variable renewable energy contributing up to 90% of the energy resource mix. These scenarios were then evaluated assuming any firm dispatchable resources were highly flexible to estimate the capacity and energy needed to ensure reliability after accepting all the solar, wind, and battery energy storage that the system could accept.

The scenarios and flexible 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 25-year period, creating dispatch profiles for nearly 184,000 hours of chronological operations. The firm capacity requirements for one week of high solar resource and one of low solar resource are shown in Figure 1.

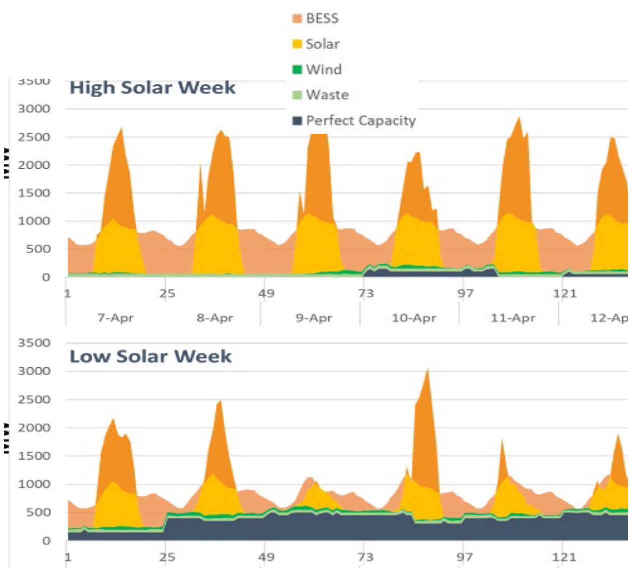


Figure 1. Representative high and low solar weeks and the need for firm renewables.

The analyses yielded the amount of curtailment of variable wind and solar resources, as well as the utilization of the firm-flexible capacity resource. Particular attention was given to the maximum dispatch of the firm-flexible units, which implies the capacity need. Operational metrics like number of starts, ramp needs, operating hours, and capacity factor by incremental block were also evaluated.

Results of the analysis are provided in Figure 2, showing the maximum firm-flexible capacity requirement as a percentage of peak load (y-axis) at varying levels of solar and storage builds (x-axis). These values can be used as a proxy for the firm renewable resource needs of the system.

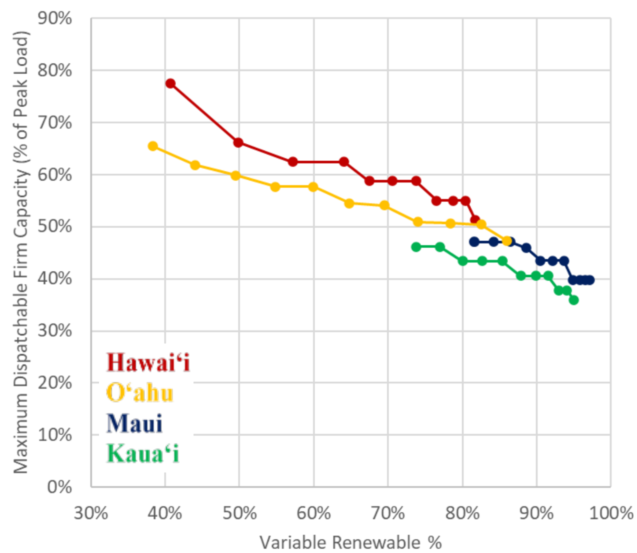


Figure 2. Minimum firm capacity needs by island at increasing levels of variable renewables.

The analysis found that even at very high penetrations of variable renewable energy, there is still a substantial need for firm capacity. With 70% of the annual energy demand met by variable resources, the system still requires firm-flexible capacity of approximately 60% of the system's peak demand. While higher levels of variable generation reduce this requirement, there are diminishing returns associated with the additional variable renewable energy at high penetrations and the additional cost of increasing curtailment.

In 2024, the HNEI project team updated this analysis to evaluate the impacts of solar forecast accuracy and the operating flexibility of the new firm resources on the maximum capacity required to maintain reliability. Quantifying this flexibility need and gaining community acceptance of the results is critical given the lead time for new generation resources.

This new study is evaluating three types of firm resources: 1) baseload resources which are unable to cycle on or off or load follow; 2) inflexible resources which have significant startup/shutdown times and limited ramp rates; and 3) fully flexible resources that could start/stop and ramp quickly. An illustration of these three configurations and the impact on one week of operations is provided in Figure 3.

Results of this analysis indicate that when forecast errors of solar resources are introduced, quick-start flexible resources are more effective at meeting the firm energy needs. Without highly flexible firm generation, early firm unit commitments are required, introducing the likelihood of increased curtailment or resource adequacy shortages, depending on the accuracy of the solar and wind forecast.

Today, there are limited low-emission resources available to provide dispatchable firm capacity, and each has operational limitations and cost/availability issues that must be considered. While identifying the optimal firm flexible technology is not part of this analysis, the large capacity needs identified shows the need for more attention to this issue. HNEI is initiating a number of studies, some in concert with the Hawaiʻi Energy Policy Forum (Appendix A3), to address the options.

This study is intended to be a screening analysis of the firm renewable capacity needs for future Hawaiʻi grids to help inform legislation and utility procurements. This work will be presented to the Hawaiʻi Energy Policy Forum to initiate a broader discussion of these grid needs. 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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2024

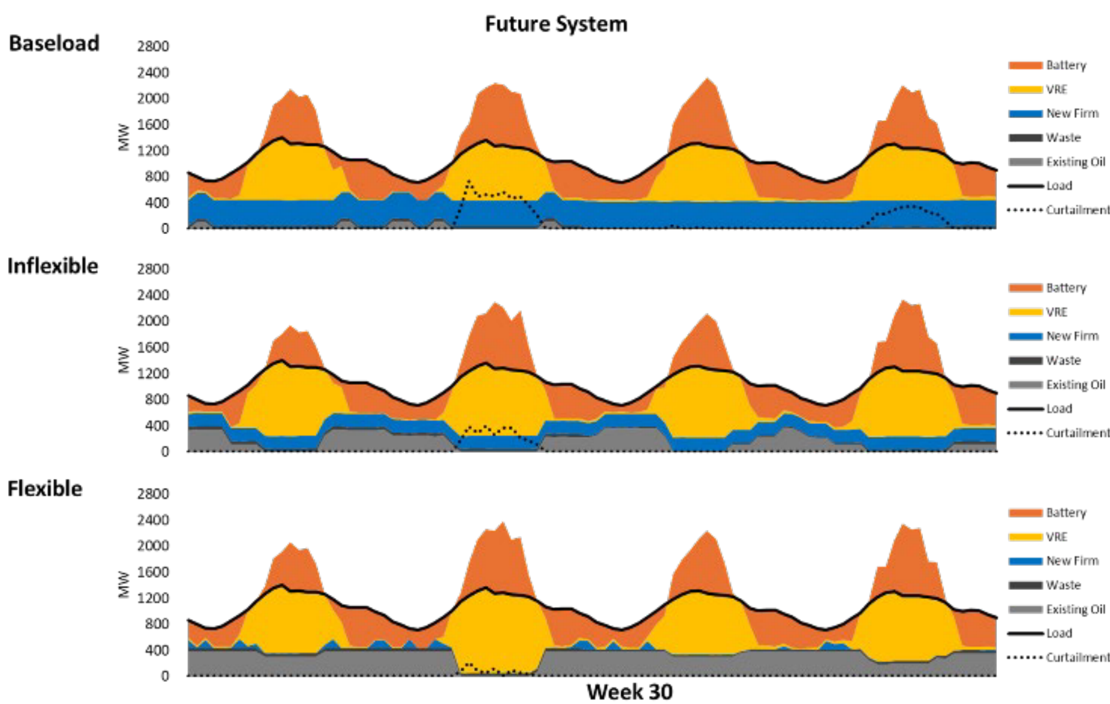


Figure 3. Weekly dispatch of system with baseload (top), inflexible (middle) and flexible (bottom) firm resources.

B3: Recent Reliability Challenges

OBJECTIVE AND SIGNIFICANCE: HNEI regularly monitors grid operations and hourly generation data provided in PUC dockets and provides independent reviews of reliability events. Recently, the Hawaiʻi's power grids have faced some reliability challenges (resource adequacy). An assessment of the most recent events indicates that the transition to renewable energy is not to blame. Rather, higher than normal failures at oil-fired power plants have challenged grid reliability on Oʻahu and Hawaiʻi Island. The new solar and storage systems are emerging as valuable assets for maintaining reliability.

KEY RESULTS: Recent reliability events on Oʻahu occurred during a period of cloudy weather with low solar and wind generation, but the lower than usual energy available from renewables was not the cause. Instead, the rolling blackouts were due to unexpected outages of several of the utility's oil-fired generating plants at a time when several other generators were offline for maintenance. In July 2024, the utility asked for conservation due to higher than usual risk of a generation shortfall due, again, to an unexpected loss of generation. However, during this, the new solar and storage resources played a crucial role in supporting grid reliability.

BACKGROUND: In the early winter and spring, the electric grids on Oʻahu and Hawaiʻi Island experienced rolling blackouts. These rolling blackouts occurred because of island-wide generation supply shortages. Simply stated, there was not enough generation or stored energy available on the island to serve the demand. This occurred four times recently: once on Oʻahu (January 8th) and three times on Hawaiʻi Island (January 30th, February 13th, and April 15).

More recently, the Oʻahu power grid had another close call on July 31st when calls for conservation were initiated by the utility due to anticipated energy and capacity shortfalls. However, rolling blackouts were avoided and customers were not impacted due to the availability of energy from the batteries.

These types of reliability events, referred to in the power industry as resource adequacy shortfalls, are exceedingly rare on the mainland, where grids are larger and more interconnected. While still rare in Hawaiʻi, they do occur more often because the island's grids are smaller and isolated from neighbors. On Oʻahu, for example, planners design to expect no more than one shortfall every four years.

PROJECT STATUS/RESULTS: Over the past year, HNEI has been analyzing utility operating data, including hourly load and generation by power plants. The project team tracks generator performance, outage rates, maintenance schedules, and operating reserves.

This analysis revealed that while the January 8th outages on Oʻahu occurred during a period of cloudy weather with low solar and wind generation, the availability of energy from the variable renewables was not the cause. Instead, the rolling blackouts were triggered by unexpected outages of several of two of the utility's oil-fired generating plants, at a time when others were offline for maintenance. During this event, Hawaiian Electric Company (HECO) lost significant generation capacity in quick succession due to flooding at the Waiau power plant and failures at the H-Power waste-to-energy plant.

The July 31st reliability event was caused by sequential generator outages over a period of days at HECO's three largest power plants. This sequence of events is discussed in more detail below.

Whether due to age alone or a combination of other factors, the utility's generators are facing increasing maintenance needs and more frequent mechanical failures. The decreasing reliability of these plants, as measured by how often they become unavailable without warning, is posing a significant challenge to the utility. Figure 1 shows the percentage of firm generation, weighted by capacity, which was on unexpected, forced outage each year since 2007. On Oʻahu, this "weighted forced outage' rate has increased from below 5% in 2007 to 20% in 2023.

On July 31st, the day of the most recent call for conservation on Oʻahu, only 700 MW (less than half) of the island's oil-fired power generation was available. With peak demands reaching up to 1000 MW during the evenings, the grid found itself unable to rely on its usual generation capacity to meet the demand. Figure 2 illustrates the available capacity on Oʻahu from oil-fired generation (gray bars) relative to the hourly load (black line) from July 29th to July 31st.

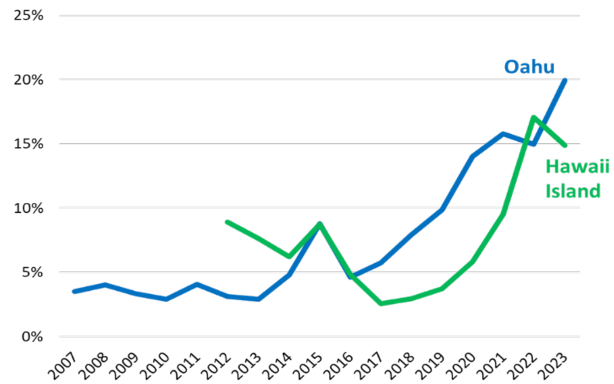


Figure 1. Increasing unavailability of HECO firm generators due to unplanned outages.

Although thermal generation was experiencing unexpected outages, the solar and storage plants performed effectively during critical evening peak demand hours, playing a crucial role in serving the grid's energy needs (Figure 3). Throughout the evening hours, when the oil-fired power plants alone could not meet the demand, these hybrids solar + storage and standalone storage systems provided the necessary power to avoid rolling blackouts.

As more fossil-fueled resources are retired, batteries and renewable energy systems will be increasingly important in ensuring grid reliability. The July 31st event demonstrates that with the right planning and effective operation, renewable energy can not only provide energy to the grid but can also provide essential reliability services during critical times.

HNEI will continue to monitor grid operations and reliability across the Hawai'i power grids and intends to share its findings with the PUC, the utility, the Hawai'i Energy Policy Forum, and the interested public.

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2024

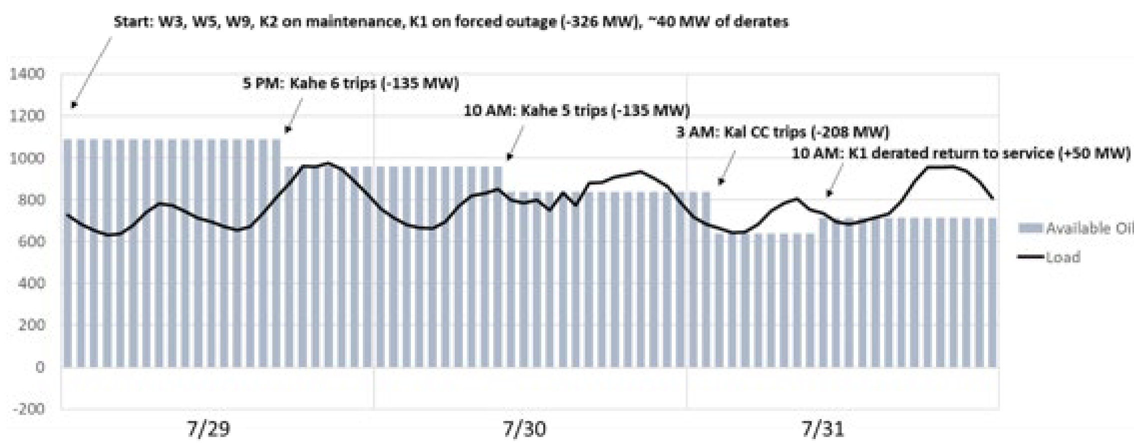


Figure 2. Available capacity from oil-fired power plants declined throughout the week of July 31.

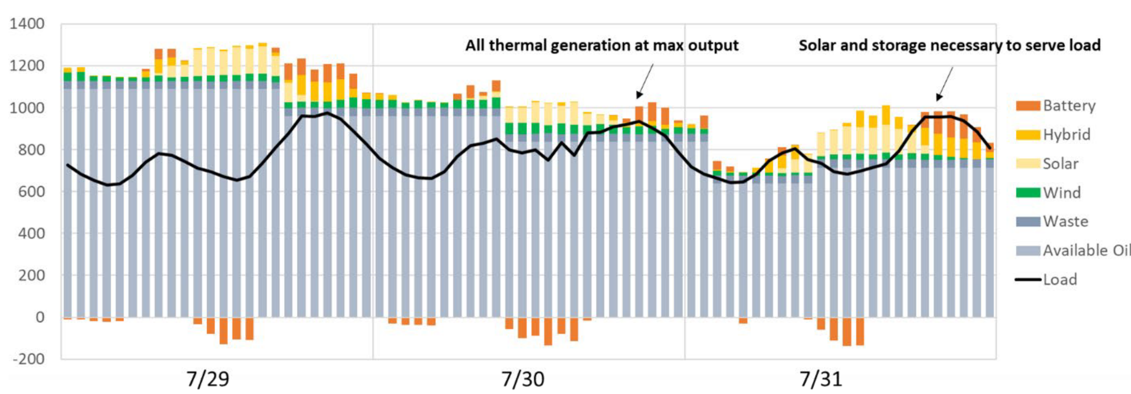


Figure 3. Hybrid and battery resources fill the gap and maintain reliability during critical evening hours.

B4: Hydrogen to Meet Firm Power Needs in Hawai‘i

OBJECTIVE AND SIGNIFICANCE: In December 2023, HNEI provided a report to the legislature on the potential production and use of renewable hydrogen in Hawai‘i to inform the H_2 Strategic Plan. The study identified several potential use cases for hydrogen to meet Hawai‘i's decarbonization goals, including using hydrogen for firm power generation.

Previous HNEI work and long-term utility planning has determined there will be a need for firm dispatchable power generation to support a 100% renewable energy system. To assess hydrogen's ability to serve this need, HNEI evaluated the energy, and infrastructure needs to produce hydrogen using water electrolysis, store it, and convert it back to electricity to meet long-term firm power needs by supplying 5% of Hawai‘i's 2045 annual electricity demand.

KEY RESULTS: Results of this analysis show that while it is technically feasible for hydrogen to provide firm power needs, there are substantial energy and storage infrastructure hurdles that are unique to the islands. Producing hydrogen using electrolysis is extremely energy intensive.

Results indicate that under optimistic technology performance, meeting 5% of statewide electricity demand using hydrogen would require annual electricity generation to increase by 21-27% when accounting for energy to enable storage. Whether produced by solar, wind, or geothermal, O‘ahu would be land constrained. Providing hydrogen to O‘ahu would require production and transport from one of the neighbor islands.

While hydrogen may have niche applications in Hawai‘i's energy future, high production costs, the need for seasonal storage challenges, and shipping and transportation challenges/needs make it impractical for widespread use for firm power.

BACKGROUND: Hydrogen has received significant attention as a potential solution for decarbonizing various sectors in Hawai‘i's economy. Legislative initiatives such as HB 1611 and HB 1937 reflect a strong interest in exploring hydrogen's potential. HB 1611 proposed a State Energy Plan emphasizing firm renewable energy options, including hydrogen, while HB 1937 tasked the Hawai‘i Natural Energy Institute (HNEI) with evaluating hydrogen production from local renewable resources. This analysis included considerations, such as water usage, system costs, feasibility of end-use applications, and hydrogen's role in the grid. These issues are addressed in HNEI's 2023 "Report on the Potential Production and Use of Renewable Hydrogen in Hawai‘i."

National interest in hydrogen has surged following the passage of the Inflation Reduction Act (IRA), which introduced incentives for clean hydrogen hubs, intended to connect hydrogen consumers and producers. While Hawai‘i did not receive hydrogen hub funding, recent federal funding announcements continue to signal interest in hydrogen development in the state. A $56.7 million award to the Hawai‘i Department of Transportation was recently announced by the EPA to support hydrogen cargo handling equipment and associated storage and fueling infrastructure at Honolulu Harbor.

With the ongoing state interest in hydrogen, the HNEI-Telos team has continued to monitor developments to assess viability for Hawai‘i.

PROJECT STATUS/RESULTS: Deploying hydrogen for firm power generation in Hawai‘i presents three primary challenges:

1. **Energy Intensity of Production**: Producing hydrogen via electrolysis requires substantial amounts of energy, adding to the already significant demand for renewable electricity.
2. **Seasonal Storage Requirements**: Hydrogen storage would need to shift large amounts of energy from renewable-rich periods (spring/summer) to low-renewable, high-demand periods (fall/winter) – necessitating costly infrastructure.
3. **Inter-Island Transportation**: O‘ahu is unlikely to have the land availability to produce hydrogen at scale on its island. Transporting hydrogen between islands would further increase logistical complexity and costs.

Due to limited local resources, alternative hydrogen production methods, such as from crops or waste streams, are infeasible to meet firm power needs in Hawai‘i.

Approximately 54 million kilograms (kg) of hydrogen would need to be produced annually to meet 5% of Hawai‘i’s projected 2045 electricity demand (700 GWh/year). Electrolyzing this volume of hydrogen and converting it back into electricity would require 3,000 GWh/year of clean energy – representing a 27% increase in clean energy generation over the current estimated electricity demand. The low efficiency (24% round-trip) stems from losses in electrolysis (60%) and hydrogen combustion for electricity generation (40%), with additional losses due to needing liquid hydrogen for bulk storage.

Producing this amount of hydrogen using clean energy would require:

- 1,500 MW of solar PV (2x existing capacity, including rooftop solar);
- 860 MW of wind (4x existing capacity); or
- 360 MW of geothermal (10x existing capacity).

While Hawai‘i is blessed with a good year-round solar resource, there is significant seasonal variability. The use of hydrogen for firm power would result in a net production in the summer and a net consumption in the winter. Figure 1 shows weekly net hydrogen production (blue) and consumption (red) over a single year. A clear seasonal shift of energy from summer and spring months to fall and winter months is shown.

The mismatch between production and consumption shown above drives the need to consider hydrogen storage when assessing the use of hydrogen for firm power generation. In this example, O‘ahu requires peak hydrogen storage of 18,000 metric tons, equivalent to approximately 54 of NASA’s largest 330 metric ton liquid hydrogen storage tanks. Hawai‘i does not possess the type of geologic storage that some regions on the mainland may benefit from to reduce bulk storage costs and gaseous hydrogen storage is impractical at the scale discussed here.

This study will continue to inform economic and energy planners on the impact that integrating hydrogen production will have on Hawai‘i’s grid.

REFERENCES:
[1] HNEI, Report on the Potential Production and Use of Renewable Hydrogen in Hawai‘i, under Act 140, SLH 2022 and SB 2283, December 2023

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2024

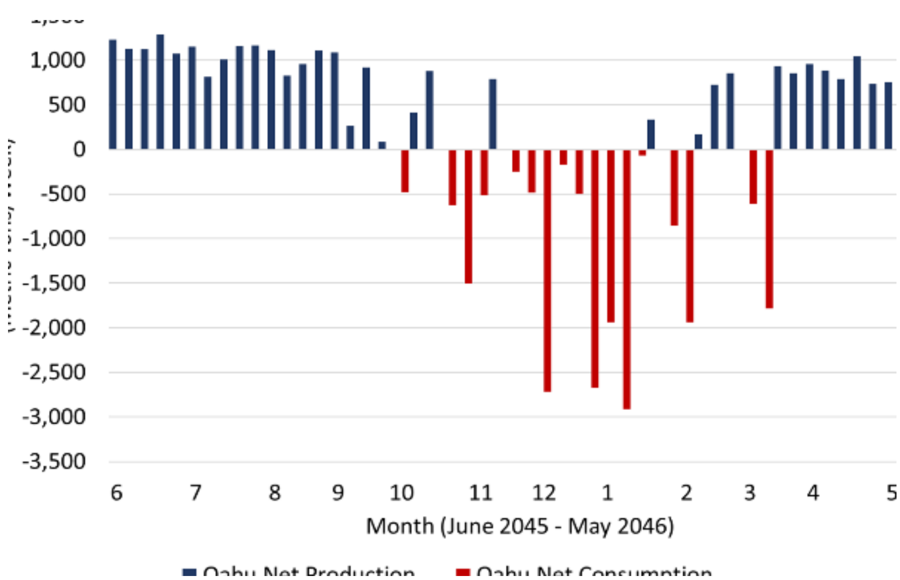


Figure 1. Weekly net hydrogen production for delivering 5% of O‘ahu electricity in 2045.

B5: Analysis of TOU Rates and Load Flexibility

OBJECTIVE AND SIGNIFICANCE: Time-of-use (TOU) rates – electric rates that vary based on the time of consumption – are currently being developed and implemented on a trial basis by HECO and the Hawaiʻi Public Utilities Commission (HPUC). Under the new rate structure, electricity prices during evening peak demand periods would be three times that in the middle of the day. The objective of this study was to assess whether the load shifting intended from the implementation of time-of-use rates would reduce grid operating costs given recent deployment of battery storage. Preliminary results of this study were presented to HECO and shared with the HPUC in 2023. HNEI has continued to monitor the activities throughout 2024.

KEY RESULTS: TOU rates are a tool that uses price signals to encourage load shift to the middle of the day. Analysis of Oʻahu grid operations show that shifting load from the 5pm to 9pm peak period to the daytime would not meaningfully reduce the overall cost of generation (i.e. production cost) once significant amounts of grid-scale batteries are added. The analysis showed that the operational restrictions limiting the integration of more solar and the need for expensive peak demand resources are both diminished as a result of the addition of grid-scale batteries. As a result, the cost savings expected by swapping expensive peak generation with low-cost solar generation no longer exists.

BACKGROUND: With advances in distributed energy resources (DER) technologies and the proliferation of smart devices, customer load can adjust to better align with the capabilities of the power system. The HPUC and HECO has pursued a variety of initiatives to provide load flexibility or to shift load, including advanced rate design (time-of-use rates), DER Phase 3 program design, and a competitive solicitation of grid services (i.e. Maui Grid Services RFP, which received no bids). While having a common goal of managing load, each of these programs impacts the power system differently.

TOU rates, like those currently being proposed have been under development by HECO in 2012 (TOU-R). Since then, the power system has changed remarkably and the type of load shifting needed has changed. Between 2023-2025, each of the HECO grids will see large increases in battery storage – both in standalone projects as well as utility-scale solar + storage hybrid projects.

HECO and the HPUC have already committed to these large battery projects in recent procurements and most of them are either already operating or under construction. On Oʻahu, for example, battery storage will soon reach 400 MW of capacity, over one-third of evening peak load, with more coming in the current procurements. The storage deployment on other islands is similar or even more pronounced on a proportional basis.

The objective of this analysis is to evaluate and compare the system cost savings of TOU rates in legacy grid systems with those in systems that have a high penetration of batteries.

PROJECT STATUS/RESULTS: The HNEI-Telos team analyzed the impacts of TOU rates on Oʻahu's system, a variety of load flexibility options on Maui's system, and, as a final step, assessed how the proposed rates may shift costs across ratepayers.

The evaluation of the potential benefits of TOU rates on Oʻahu focused on the potential fuel cost savings assuming a 20% shift of residential evening load to the middle of the day. An evaluation of potential reliability benefits and impacts on oil plant retirements attainable due to reduced peak load has also been initiated. This summary will focus on the cost issues.

To assess the impact of TOU, system production costs were evaluated across three scenarios: 1) grid operations prior to utility-scale storage additions; 2) a "2025" grid that includes the currently planned solar and storage additions; and 3) a higher solar and storage portfolio representative of the state's 2040 goals. The evaluation of these three scenarios allows for a quantitative comparison of benefits of potential load shifting.

The study found that TOU rates offer minimal fuel cost savings on Oʻahu. The reason for this is two-fold. First, while solar generation is abundant in the middle of the day, there is limited curtailment in all three scenarios. Therefore, shifted load will be served almost exclusively by oil generation, not by the uptake of curtailed solar, albeit with a modest improvement in fuel efficiency. Second, energy losses from load shifting (via behind-the-meter batteries, pre-cooling of evening air conditioning, or otherwise) leads to a slightly increased electricity usage overall, tending to balance the modest efficiency gains.

TOU rates are designed, in large part, to reduce the need for "peaking" generators that are built to run sparingly, in times of high load and when needed for reliability. In theory, any resulting load shifting could reduce peak demand and avoid the need for new "peakers" or enable oil plant retirements. However, especially in the near-term and future scenarios, the peak capacity needs will be met with already approved and under construction battery storage additions.

It has been proposed that TOU rates that discourage energy use from 5pm to 9pm could reduce the risk of resource shortfalls. However, preliminary results indicated that with significant battery deployment, risk is spread evenly across the day and load shifting would have minimal impact on reliability. Further work to assess firm power needs under differing load profiles is continuing.

Similar analysis has been conducted for Maui. While the current resource mix on Maui does not yet include large amounts of energy storage, significant additions are planned under the Stage 1, Stage 2, and Stage 3 procurements resulting in minimal impacts from load shifting due to TOU rates. In light of the expected retirements of a significant part of Maui's generation, analysis is ongoing to evaluate the impact of all types of load flexibility on reliability.

Rate Impact: While TOU rates will have limited system benefits once the planned battery systems are deployed, they will create significant changes to the way electricity is billed, and potentially create equity concerns. To evaluate this further, the study assessed individual customer impacts of the proposed TOU rates. This included a review of individual 15-minute advanced metering data across 60,000 customers for a single month. The results showed that large proportions (85+%) of non-PV customers would be Structural Winners – those who would get a cheaper bill just from switching to TOU rates, even without changing their behavior.

Customers with PV, in contrast, would see a significant increase in monthly bills (62% or $82/month on average) if they were required to switch to TOU rates (note that forcing legacy PV owners to switch to the new rate is highly unlikely). Even if the TOU rate successfully encourages behavior change, the only outcome is that some customers save money, but provide limited system benefits. The reduced revenues would have to be made up with increased rates overall to maintain revenue neutrality, disproportionately affecting customers with less ability to shift consumption during low price periods.

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

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

Contact: Richard Rocheleau, rochelea@hawaii.edu

Last Updated: November 2024

Hawaiʻi Natural Energy Institute Research Highlights

Appendix C: Grid Technology Development

C1: Coconut Island DC Microgrid

<u>OBJECTIVE AND SIGNIFICANCE</u>: HNEI's Grid System Technologies Advanced Research Team (Grid*START*) has developed a DC-based microgrid test bed on Coconut Island, home to the University of Hawaiʻi's Hawaiʻi Institute of Marine Biology (HIMB). This project aims to demonstrate and assess the reliability, resilience, and energy efficiency of a DC microgrid serving two HIMB buildings. It will compare the efficiency of powering lighting, cooling, and plug loads with AC versus DC electricity during normal operations. Additionally, the microgrid will support critical building loads during grid supply interruptions and provide clean transportation options, such as an electric boat powered primarily by rooftop solar energy. The findings from this project can inform future DC-based microgrids in Hawaiʻi and beyond.

Figure 1. DC microgrid project site, Coconut Island.

<u>BACKGROUND</u>: HIMB aims to serve as a model for sustainable systems, making it an ideal location for a microgrid test bed focused on renewable energy technology. Key objectives include implementing innovative and efficient clean energy technologies, creating a research platform for resilient DC microgrid technologies in a tropical coastal environment, and advancing solar-powered transportation solutions.

<u>PROJECT STATUS/RESULTS</u>: HNEI collaborated with the University of Indonesia (UI), which designed a new DC-DC converter (DCON) that transforms the voltage from the photovoltaic (PV) and battery energy storage system (BESS) 48 V DC bus to the 200-350 volts needed for various microgrid loads. The microgrid powers DC lighting, DC air conditioning, refrigeration, and other high-priority critical loads with minimal reliance on the grid, even during peak demand.

All components of the DC microgrid system have been successfully installed and commissioned in a dedicated electrical room. This room contains essential electrical components such as switches, breakers, controls, a BESS, DC-DC converters, and associated wiring. The 6.2 kW rooftop solar PV system and 8 kWh BESS have been seamlessly integrated into the DC microgrid. With the system controller properly programmed, the DC microgrid is fully operational and undergoing performance testing across a range of scenarios, including providing resilient energy supply to critical load centers in islanded mode.

Figure 2. DC microgrid components in the dedicated electrical room (left) and system's controller box (right).

HNEI Grid*START* upgraded the system with significant improvements. A real-time monitoring dashboard was developed for 24/7 on-site monitoring. The electric boat's performance was improved by upgrading to 18.2 kWh fixed batteries from 11.2 kWh swappable ones, while additional rooftop PV panels increased its charging capacity. To further improve resiliency, plans are underway to add bidirectional charging capability for the electric boat, which is expected to increase the microgrid's generation capacity by about 30% and triple its storage capacity. Initial lab tests for this unique functionality have been successfully completed.

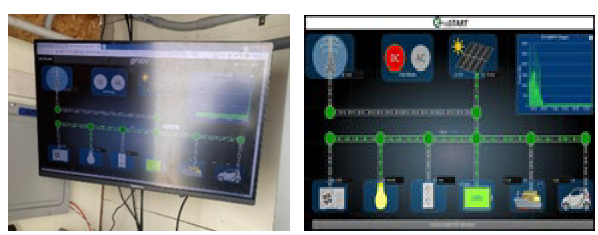


Figure 3. On-site dashboard and its screen.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

C2: Advanced Conservation Voltage Reduction Development and Demonstration

OBJECTIVE AND SIGNIFICANCE: HNEI's Grid System Technologies Advanced Research Team (Grid*START*) is demonstrating advanced conservation voltage reduction (CVR) at a U.S. Marine Corps (USMC) base in Okinawa, Japan. CVR reduces energy consumption and peak demand by seamlessly lowering voltage levels within acceptable ranges on distribution circuits.

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

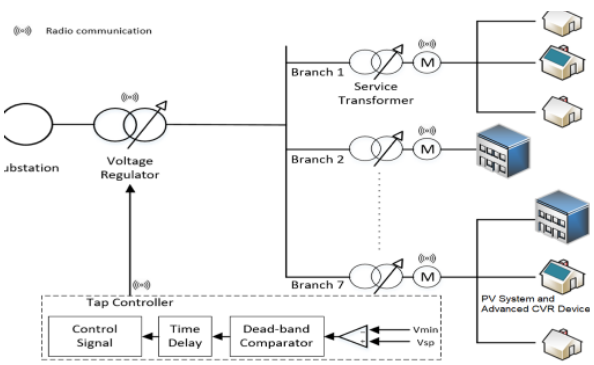


Figure 1. CVR demonstration system architecture.

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

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

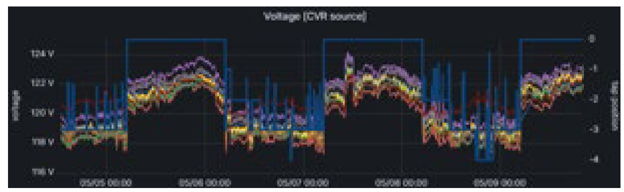


Figure 2. Voltage profiles with CVR on and off. The tap position (blue) at 0 indicates CVR is off.

In response to evolving cyber security requirements, the CVR system was separated from the USMC's AMI network. While the system faced challenges when typhoon Khanun caused a seven-month VR outage, operations have since resumed. Further maintenance issues were addressed with new hardware installed for the advanced CVR device during a planned feeder outage in October 2024. Moving forward, HNEI will focus on evaluating system coordination and analyzing CVR benefits across the various end-use load classes served by the project.

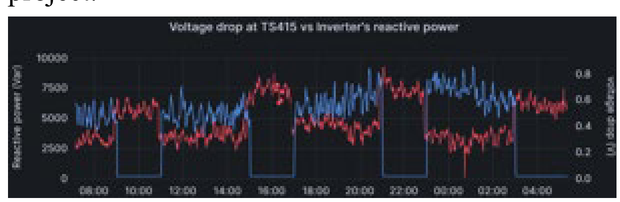


Figure 3. Voltage drop (red) is reduced when the advanced CVR controller is enabled, and reactive power (blue) is dispatched.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

C3: 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). Its primary goal is to assess the economic value and operational effectiveness of customer-sited battery and solar (BESS+PV) resources, where these resources can simultaneously serve both the customer's interests and needs of the grid when aggregated as part of a virtual power plant (VPP). The significance of this initiative lies in its potential to reduce customer electricity costs while enhancing grid operator demand response capabilities, providing valuable insights into the effectiveness of incentive-based VPP programs.

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

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

PROJECT STATUS/RESULTS: HNEI developed optimization algorithms that integrate building energy load and rooftop solar power generation forecasts. This system optimizes charging and discharging schedules of BESS units, thereby reducing electricity costs for building owners while meeting utility-initiated demand response requirements. A methodology was created to evaluate potential benefits of customer participation in Hawaiian Electric Company's VPP program, which uses an incentive-based demand response scheme. Figure 2 illustrates the system overview.

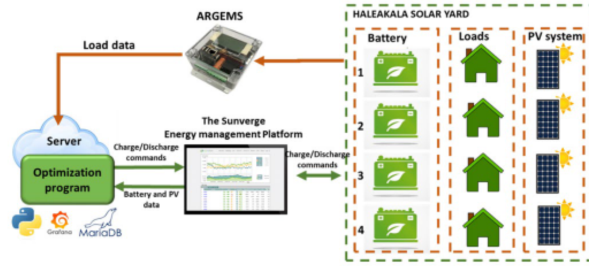


Figure 2. System overview of the VPP program.

Additionally, a web-based dashboard (Figure 3) was developed for real-time monitoring and data collection of SIS BESS+PV units.

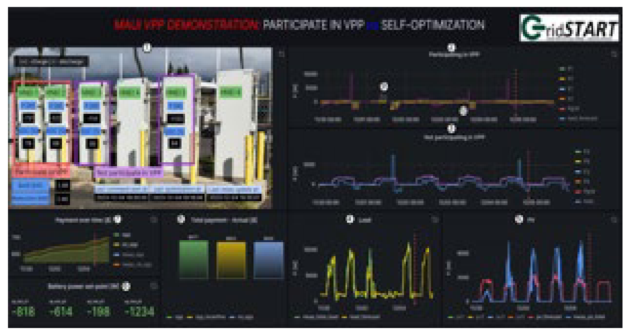


Figure 3. Web-based dashboard interface.

Using collected real-time data, HNEI Grid*START* tested the optimization algorithms for two scenarios: participation in the VPP program and non-participation. Results indicated that customers benefit from reduced electricity costs when participating in the incentivized VPP program with BESS optimization, compared to BESS optimization cases without VPP program participation.

The integrated tool, comprised of the optimization system, methodology, and dashboard, illustrates the financial incentives and aids customer decision-making regarding VPP participation. The project has also contributed to academic literature, resulting in two published conference proceedings papers. Following the project's field operational completion in August 2024, HNEI aims to expedite the finalization of equipment decommissioning, removal, and reporting in the subsequent months.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

C4: Assessing Dynamic Response of Converter-Dominated Power Systems

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

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

Project Status/Results: HNEI has made significant progress in developing a comprehensive PowerFactory model for detailed RMS and EMT studies at the NELHA Research Campus (RC) site. A major part of this effort was modeling nonlinear loads, which involved sophisticated data analysis techniques applied to recordings from micro phase measurement units (μPMUs) installed on-site. Additionally, VFD loads and PV systems were accurately modeled using operational data from NELHA's SCADA system, supplemented by specifications from equipment datasheets. This process was essential for deriving precise parameters for harmonic sources, crucial for fine-tuning the RMS and EMT models. Also, to address the site's specific power patterns, which include 204 kW of PV inverters active during the day and idle at night, along with the continuous operation of large VFD-based pumps, two sets of models were developed: one for daytime and another for nighttime. This diurnal variation was captured to thoroughly assess the microgrid's performance under different operational scenarios. Subsequently, these models were rigorously validated against the recorded data to ensure their accuracy.

For this project, the team made several trips to the project site on the Big Island. The figure below shows a team member as he configures the final settings of the project's μPMUs at the site. Measurements from these meters were crucial for fine-tuning the RMS and EMT models for both daytime and nighttime operations.

Figure 1. Team member adjusting project's meters.

Funding Source: Department of Energy

Contact: Saeed Sepasi, sepasi@hawaii.edu

Last Updated: November 2024

<u>**OBJECTIVE AND SIGNIFICANCE**</u>: This project aims to develop, evaluate, and demonstrate the performance of novel algorithms to optimize the charge/discharge of shared fleet vehicles for energy cost minimization. Project results will advance energy research and also inform the university's consideration of options such as the electrification of fleet vehicles, advanced car share applications, integration of distributed renewable energy resources on campus, and the optimal management of campus energy use and cost containment.

<u>**BACKGROUND**</u>: HNEI's Grid System Technologies Advanced Research Team (Grid*START*) partnered with IKS Co., Ltd. (IKS) on technology development, testing, and demonstration of advanced control of two bidirectional electric vehicle (EV) chargers or hybrid-power conversion systems (H-PCS) on the campus of the University of Hawai‘i at Mānoa (UH). These chargers are located adjacent to the Bachman Annex 6 building (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 HNEI was one of the partners.

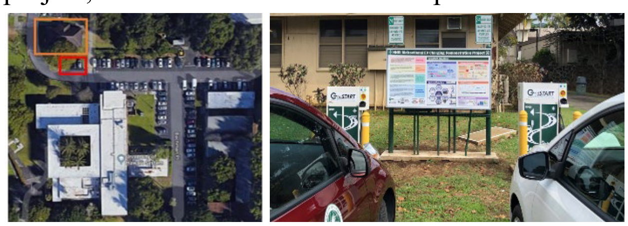


Figure 1. Location of bidirectional EV chargers.

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

<u>**PROJECT STATUS/RESULTS**</u>: The novel H-PCS control algorithms developed by HNEI first ensures that the shared vehicles for UH personnel use are efficiently assigned and readily available for transport needs. Simultaneously, the autonomous controls deliver ancillary power and energy services through intelligent EV charge and discharge commands, at times allowing the stored energy in the EV batteries to be strategically withdrawn to minimize the overall cost of energy supply to UH campus loads. The autonomous controls may also support the operational needs of the local utility operator (Hawaiian Electric Company) through the supply of grid ancillary services in return for financial compensation.

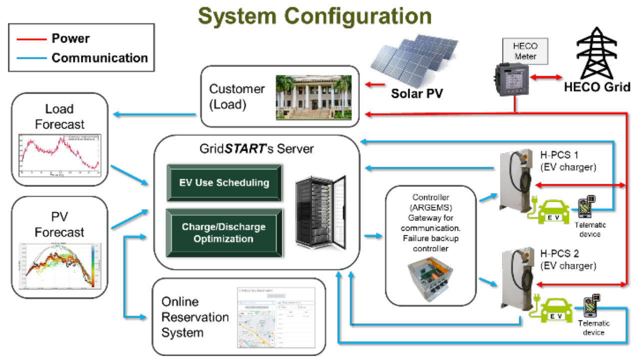


Figure 2. Functional system diagram.

HNEI'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.

Since it became field operational in July 2023, HNEI Grid*START* has made significant progress in enhancing the EV charging management system to maximize EV use and optimize charge/discharging schedules. The team has completed extensive and detailed economic analyses utilizing the scaled load demand of various campus buildings and evaluated alternative EV charging methods. Furthermore, a Machine Learning-based method using bidirectional long short-term memory network (Bi-LSTM) and least square optimization was developed to estimate energy consumption for predetermined EV trips. The team has also extended its ongoing research by developing a software-based tool to conduct techno-economic investment and sizing optimization of home energy systems (rooftop PV with BESS) with calculated financial investment payback and return, showcasing the economic value proposition of incorporating bidirectional EV charging in home applications.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

C6: EV Charging Infrastructure Master Plan for USMC Camp Fuji, Japan

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

Figure 1. HNEI personnel at CATC Camp Fuji.

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

Project Status/Results: HNEI Grid*START* and CATC Camp Fuji jointly developed an EV integration Master Plan, providing detailed technical analysis and direction for the Camp's fleet vehicle transition to EVs. The Master Plan presents two distinct approaches: 1) the Targeted Infrastructure Integration Plan and 2) the Large-Scale Infrastructure Integration Plan, with each supported by detailed schematics, cost estimates, and relevant technical data to provide Camp Fuji with flexible implementation options.

The Targeted Infrastructure Integration Plan establishes a framework for optimizing the Camp's EV fleet transition while considering current EV capabilities, Japanese public charging infrastructure, and the Camp's existing electrical systems. This approach evaluates the Camp's current fleet and facilities, identifying the most suitable vehicles and charging locations that can be electrified with minimal modifications to the Camp's existing electric infrastructure.

The Large-Scale Infrastructure Integration Plan, developed internally by Camp Fuji personnel, takes a more expansive approach by outlining the requirements for complete fleet electrification within the Camp. This plan, designed to accommodate a potential fleet of 100+ EVs, aligns with the Camp's existing Fiscal Year 2027 Energy Resilience and Conservation Investment Program (ERCIP) infrastructure improvement plans.

Both approaches provide extensive technical analyses and documentation, including schematics, concept art, electrical load information, and cost estimates for EV infrastructure integration within Camp Fuji. This level of detail enables the Camp to make informed decisions while providing a robust technical foundation for plan execution.

In February 2024, HNEI traveled to CATC Camp Fuji to present the finalized EV Infrastructure Master Plan to stakeholders within the Camp. The Plan's contents were warmly received by the Camp's personnel, with indications of prospective incorporation into future Camp developments. Following its successful reception in April 2024, this project has reached its conclusion.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

Appendix C: Grid Technology Development

C7: Automated Distribution Circuit PV Hosting Capacity Estimation

OBJECTIVE AND SIGNIFICANCE: This project aims to develop improved algorithms that significantly advance accuracy while reducing computation time for estimating the maximum capacity of distributed photovoltaic (PV) systems that can be effectively interconnected to utility secondary distribution services. The goal is to ensure that these systems can be integrated without compromising the safety, reliability, and quality of service for all customers, within the constraints of existing infrastructure and controls.

BACKGROUND: HNEI, as a subawardee to the University of Central Florida, participated in a U.S. Department of Energy (DOE) project titled "Sustainable Grid Platform with Enhanced System Layer and Fully Scalable Integration." Under this subaward, the team developed a stochastic analysis-based method for estimating PV hosting capacity of distribution feeders (Figure 1).

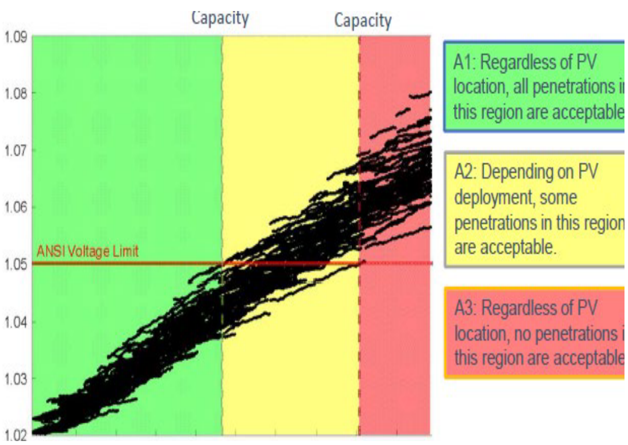


Figure 1. Schematic diagram of PV hosting capacity results.

PROJECT STATUS/RESULTS: HNEI's Grid System Technologies Advanced Research Team (Grid*START*) successfully developed a novel two-phase PV hosting capacity analysis algorithm to improve efficiency and reduce computation time. The algorithm underwent rigorous testing across various distribution and low-voltage networks, considering multiple grid operational constraints including admissible voltage limits, unbalanced voltage limits, thermal overload of distribution components, substation overloads, and power losses. This thorough and systematic evaluation ensured the algorithm's effectiveness across different network scenarios and operational conditions.

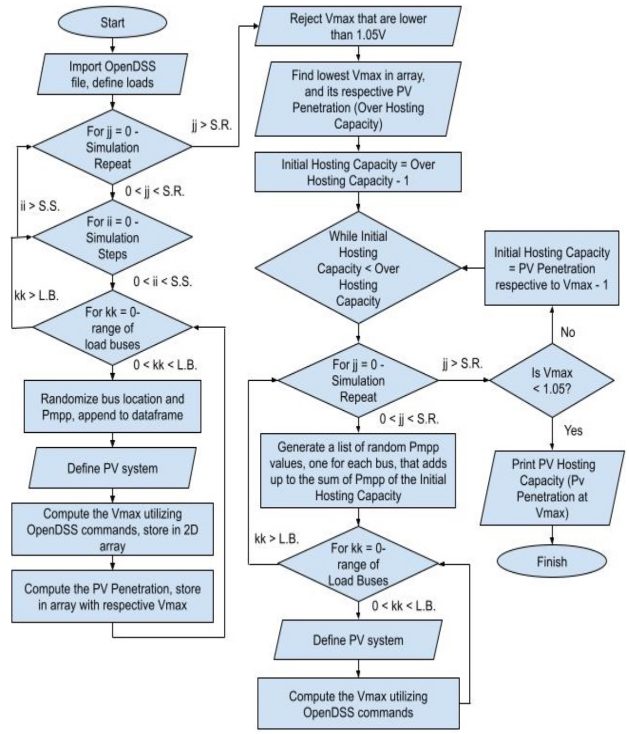


Figure 2. Flow chart of the new two-phase PV hosting capacity analysis algorithm.

The project provided valuable educational opportunities for an engineering undergraduate student to gain practical experience in distribution grid fundamentals, operational standards, OpenDSS software utilization, and Python programming for OpenDSS integration.

The research culminated in a conference paper presentation at the 2024 IEEE International Conference on Environment and Electrical Engineering and 2024 Industrial and Commercial Power Systems Europe (June 17-20th, 2024) and is pending publication in the IEEE Xplore digital library. The project is now complete following the conference's paper presentation and publication.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

C8: Holistic Optimization of Microgrids

OBJECTIVE AND SIGNIFICANCE: The primary goal of this project is to develop an adaptable and precise model for sizing microgrid systems (Figure 1), integrating various energy resources and storage technologies, such as photovoltaic (PV) systems, battery energy storage systems (BESS), hydrogen storage tanks, fuel cells, and electrolyzers. This model employs a combination of Mixed-Integer Linear Programming (MILP) and Particle Swarm Optimization (PSO) to determine optimal configurations, considering various factors, including fixed and operational costs, load demands, and PV generation profiles. The project's comprehensive approach aims to evaluate the model's efficacy against established industry tools, to minimize grid energy purchases and maximize renewable resources penetration.

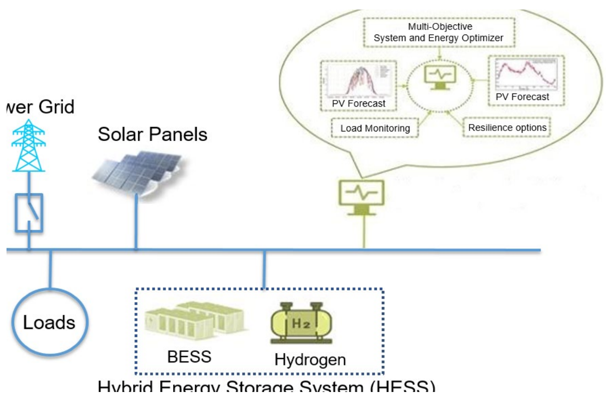


Figure 1. Microgrid with Hybrid Energy Storage (HESS).

BACKGROUND: As microgrids become increasingly crucial in modern energy strategies, our research identified a significant gap in current optimization models. This gap is particularly evident in the integration of hybrid energy storage systems with hydrogen. Traditional systems have primarily focused on both large-scale and distributed PV and storage solutions, leaving room for improvement in more complex scenarios. Our extensive review of academic literature and industry-standard tools like XENDEE and HOMER revealed a need for more advanced modeling techniques to address these challenges.

PROJECT STATUS/RESULTS: To address these limitations, we are developing an innovative model that combines two powerful optimization techniques: MILP and PSO. MILP was selected for its robust ability to define optimal solutions under complex constraints, making it suitable for diverse real-world scenarios. Its effectiveness is demonstrated in Laurence Berkeley National Laboratory's Distributed Energy Resources Customer Adoption Model (DER-CAM), and it is considered the gold standard for a variety of optimization problems. In conjunction with MILP, we are implementing PSO to enhance the model's capabilities. PSO refines the search process, guiding the system toward global optima while ensuring comprehensive exploration of potential solutions (Figure 2).

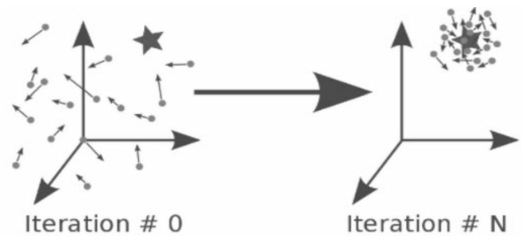


Figure 2. Particle Swarm Optimization Visual.

In our hybrid optimization model, PSO complements MILP by leveraging efficient search capabilities alongside MILP's precision. Each iteration of MILP informs PSO's heuristic function, guiding the search toward the global minimum and ensuring thorough exploration of the solution space. This integration helps avoid local minima traps and enhances the model's ability to optimize microgrid operations effectively.

Our project is currently progressing through several key stages. We are focusing on completing the development of the PSO model and will evaluate its performance using standardized PV and load profiles under normal conditions, without disruptions. Once we confirm the base model's accuracy in optimization and sizing, we will modify it to address resiliency scenarios, including critical load management, outage response, and diverse energy storage configurations. To ensure our model's effectiveness, we will conduct thorough data collection and analysis to align its performance with industry benchmarks. Finally, we plan to synthesize our findings and submit them for publication in a peer-reviewed journal that specializes in microgrid design and operation.

Funding Source: Office of Naval Research

Contact: Saeed Sepasi, sepasi@hawaii.edu

Last Updated: November 2024

D1: Sustainable Aviation Fuel Production

OBJECTIVE AND SIGNIFICANCE: In 2019, commercial aviation in Hawaiʻi used nearly 700 million gallons of jet fuel, all of it is derived from petroleum. In 2023, as the state recovered from the combined effects of the pandemic and the Lāhainā wildfire, jet fuel consumption is approaching 2019 levels (Figures 1 and 2). The University of Hawaiʻi (UH) is a member of the Federal Aviation Administration's (FAA) Aviation Sustainability Center (ASCENT), a team of U.S. universities conducting research on production of sustainable aviation fuels (SAF). UH's specific objective is to conduct research that supports developments and decisions related to supply chains for alternative, renewable, sustainable, jet fuel production in Hawaiʻi. Results may inform similar efforts in other tropical regions.

BACKGROUND: This project was initiated in October 2015 and is now continuing into its 10th year. Activities undertaken in support of SAF supply chain analysis include:

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

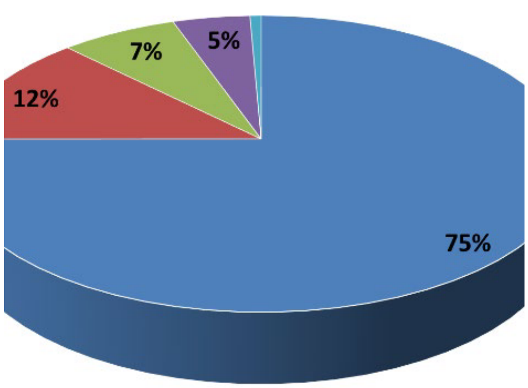


Figure 1. Commercial fuel use at Hawaiʻi's airports in 2023 totaled 638 million gallons (HNL, OGG, KOA, LIH, and ITO are Hawaiʻi's airports' codes).

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

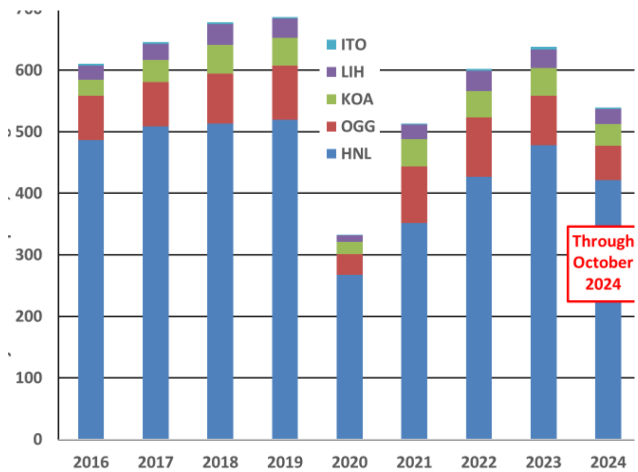


Figure 2. Commercial jet fuel consumption in Hawaiʻi.

Urban Waste: Fuel Properties of Oʻahu's Construction and Demolition Waste Streams

A sampling and analysis campaign was undertaken to characterize fuel properties of construction and demolition waste (CDW) streams on Oʻahu. Complete results were summarized and published in **Construction and Demolition Waste-Derived Feedstock: Fuel Characterization of a Potential Resource for Sustainable Aviation Fuels Production** in the *Frontiers in Energy Research* journal.

As shown in Figure 3, although the combustible fraction of the CDW samples have elevated ash levels compared to clean biomass materials, their heating values were comparable, indicating the presence of higher energy density materials. As with most refuse derived fuels, the amount of ash in the fuel and its composition is of particular importance – since ash impacts energy facility operations, maintenance, and emissions.

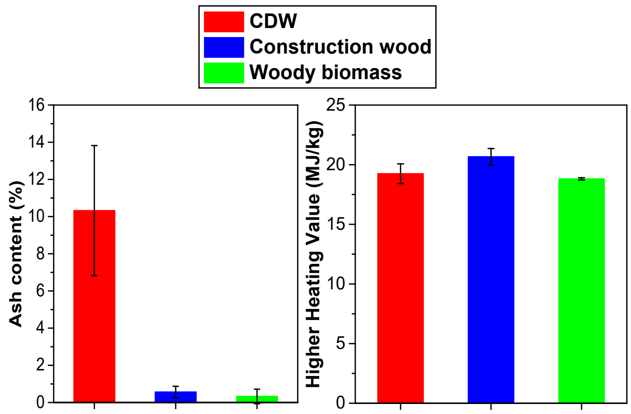


Figure 3. Ash content (left) and heating value (right) of the combustible fraction of CDW compared to construction wood and woody biomass.

Tests of clean wood fuel from the invasive species (Leuceana spp., common name koa haole) and synthetic CDW (sCDW) material were conducted at a commercial gasification technology provider facility to evaluate product composition and yields and identify contaminants (Figure 4). Test reports for koa haole ("***Gasification of Leucaena leucocephala stemwood***") and CDW ("***Gasification of synthetic CDW 1***"), respectively, are available on the HNEI website. The test results detail the reactor operating conditions, fuel characteristics, concentrations of major permanent gas species (H_2, CO, CH_4, CO_2), and concentrations of inorganic species present as contaminants in the product gas stream (H_2S, NH_3, HCl, As, Cd, Cr, Pb, Mg, P, K, Se, Na, Z, Hg). The increases of As, Pb, and Cr concentrations in the sCDW product gas compared to clean wood product gas were notable, in the case of arsenic increasing

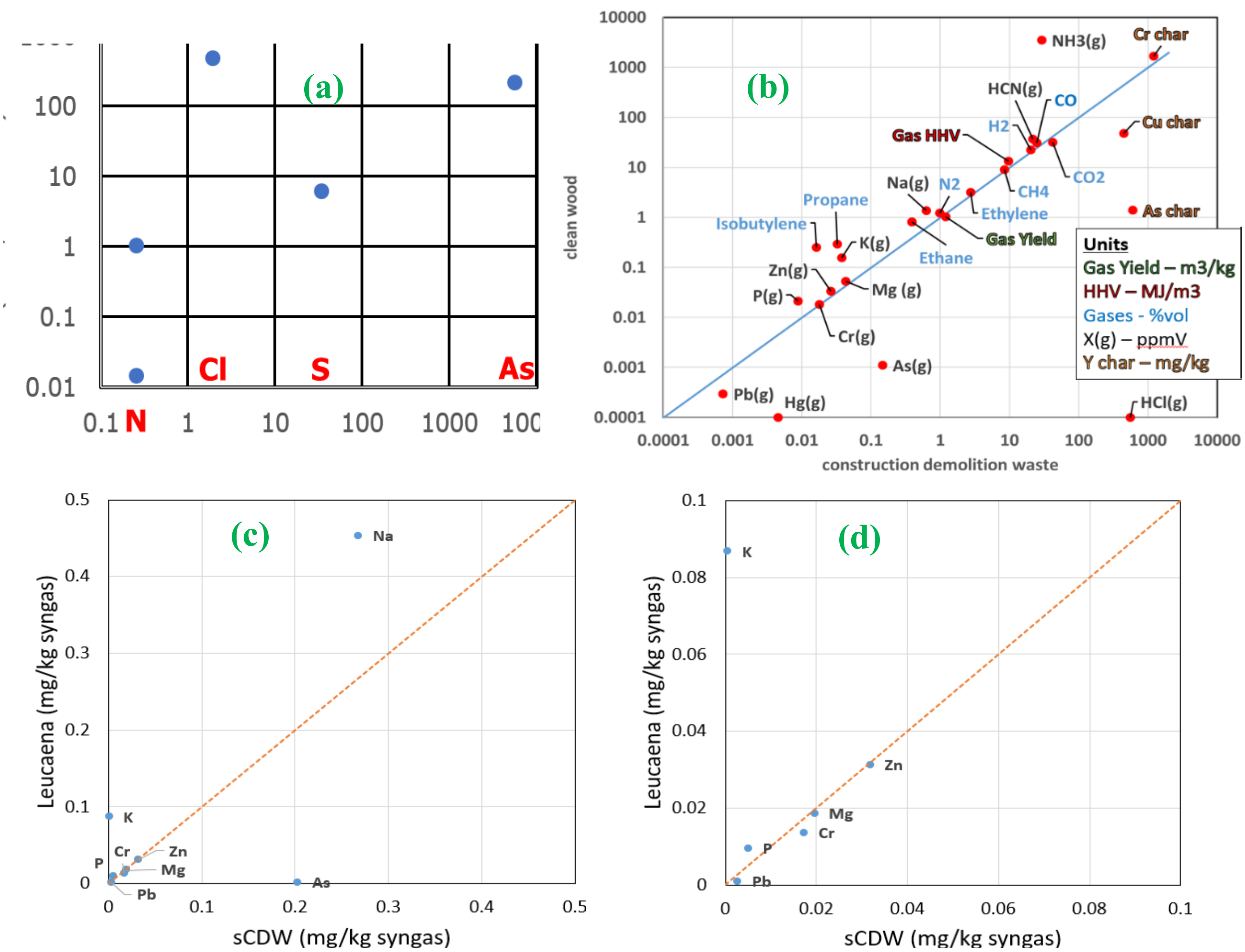


Figure 4. (a) Relative ratios of elements present in fuels to ratios in the product gas stream, (b) comparison of gasifier test measurements between clean fuel and CDW, (c) and (d).

from ~1 part per billion by volume (ppbv) to ~200 ppbv. Conversely, the clean wood fuel produces gas with elevated potassium (K) and sodium (Na) concentrations compared to the sCDW. The data indicate that managing the gas quality through feedstock treatment/blending or product gas cleanup will be required.

[1]. Waste amounts generated by counties over the past nine years are plotted in Figure 5. Waste amounts generally scale according to population, with Honolulu having the largest total despite the use of waste for fuel in the HPOWER power plant. Integrating solid waste management and SAF production with a view of treating the state as a single management unit rather than four individual county units could be a beneficial approach to meet waste management, energy resiliency, and greenhouse gas abatement goals and improve economies of scale.

Urban Waste: Resource Logistics

Utilizing urban waste resources as feedstock for SAF production has the advantages of both reducing amounts of material entering the limited landfill space and reducing dependence on imported energy. A 2022 statewide assessment of urban waste resources entering landfills is summarized in Table 1

One approach for integrated solid waste management for SAF production would transport waste resources from neighbor islands and consolidate them with waste from the City & County of Honolulu (C&C) to fuel a gasification and Fischer-Tropsch (FT) conversion facility located on Oʻahu. Figure 6 shows a schematic of this approach. Urban waste generated on Oʻahu are transported to the SAF conversion facility by trucks via transfer stations. Waste generated in other counties are transported to ports by truck, transloaded to ocean transport, shipped to Oʻahu, transloaded to trucks, and finally transported

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

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

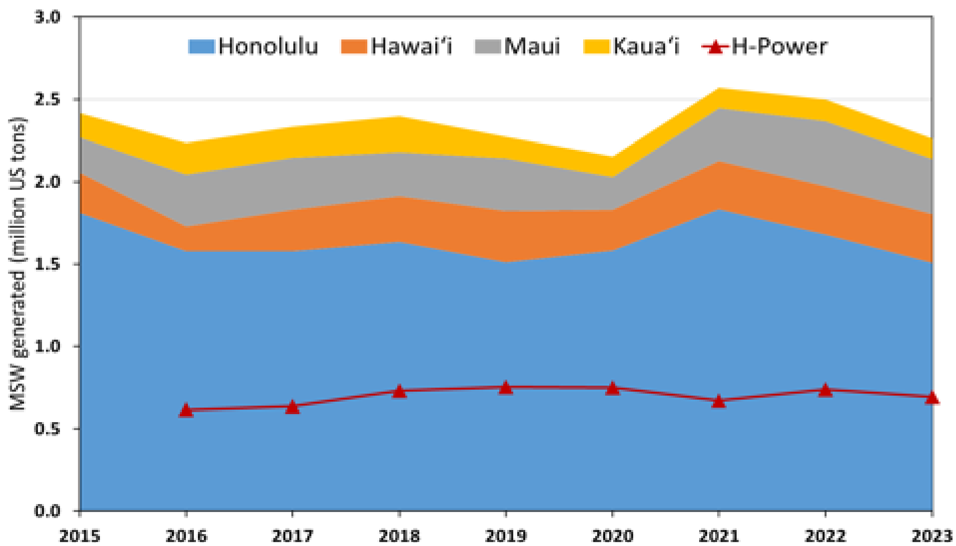


Figure 5. Annual MSW generation in Hawaiʻi by county. Data include recyclable and non-combustible materials which may not be used for SAF production.

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

to the SAF production facility. SAF is delivered by trucks to Daniel K. Inouye International Airport (HNL). Six different scenarios of non-recycled urban waste utilization for SAF production are listed in Table 2. Differences between them result from assumptions on the use of food waste and mixed plastics and the fraction of waste diverted to the HPOWER waste to energy plant currently operated in C&C. Food waste is typically a high moisture fraction of the waste stream and can be diverted for animal feed or as feedstock for anaerobic digestion. Plastics are typically the largest source of non-biogenic carbon present in waste. The remaining categories – paper, yard trimmings, combustible C&D material, mixed organics, and mixed MSW – are all included in each of the waste scenarios. All categories can be commonly identified from data included in integrated solid waste management plans prepared by individual counties.

Estimates of production potential from the six waste utilization scenarios are shown in Figure 7. Scenarios 1, 3, and 5 that don't include HPOWER operation yield the highest SAF production values ranging from 38 to 45 million gallons annually. Diverting food waste and plastics from the material fueling the SAF process accounts for the difference of 7 million gallons per year. Comparing SAF production potential under Scenarios 3 (44 million gal/yr) and 4 (21 million gal/yr) demonstrates the impact of operating HPOWER while diverting food waste but including plastic (non-biogenic carbon). Scenario 6 has the lowest SAF production potential, 18 million gal/yr, the result of diverting waste to HPOWER and excluding both food waste and plastics.

Figure 8 summarizes preliminary assessment of life cycle greenhouse gas emissions per MJ for each of the six scenarios. The results show that the estimated emissions range from 32-53 gCO_2e/MJ. As reference, petroleum jet fuel has a GHG intensity value of 90 g CO_2e/MJ. Continued operation of HPOWER reduces the amount of MSW available on O'ahu for SAF production, increasing the relative weight of MSW

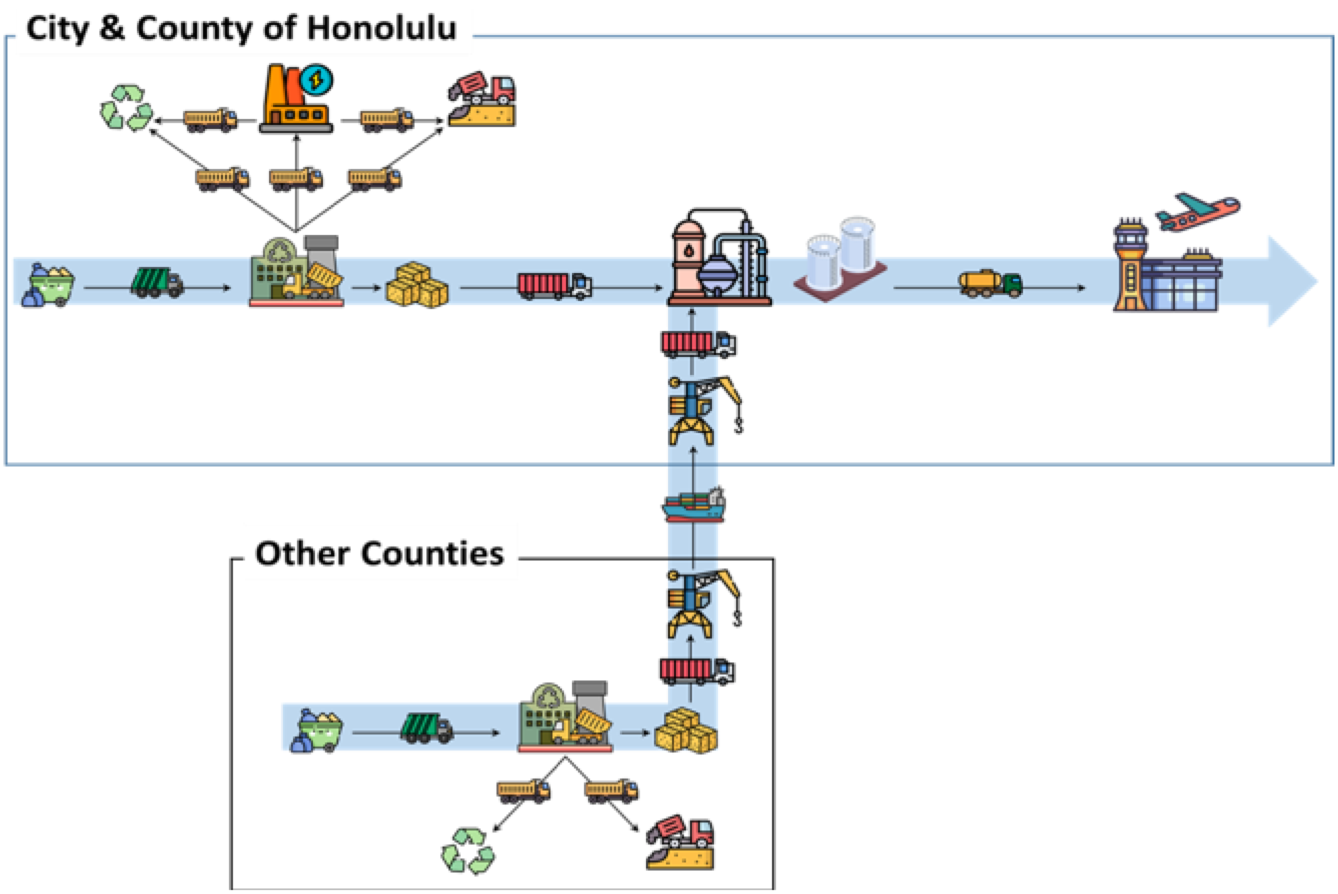


Figure 6. Schematic of waste management across the state in support of SAF production on O'ahu.

transported from outer islands and their associated GHG intensities (GHG_e per MJ) – compare Scenarios 1 and 2. Scenarios 3 and 4 consider the impact of removing food waste from the MSW feedstock coupled with HPOWER operations. Food waste is a high moisture component of MSW and may be diverted because it is a commonly used feedstock for anaerobic digestion applications and can also be used as animal feed. Food waste removal produces a small net increase in GHG emission intensity resulting from the higher percentage of non-biogenic material in the waste stream. Scenarios 5 and 6 consider removal of plastics from the feedstock stream. Although it reduces the SAF production volumes (as shown in Figure 7), it results in a much lower GHG value since plastics contain non-biogenic carbon.

Table 2. Solid waste utilization scenario assumptions for SAF production and HPOWER (Yes indicates that waste category is included or HPOWER is operated; No indicates that waste category is excluded or HPOWER is not operated.)

Scenario	1	2	3	4	5	6
HPOWER	No	Yes	No	Yes	No	Yes
Food Waste	Yes	Yes	No	No	No	No
Mixed Plastics	Yes	Yes	Yes	Yes	No	No
Combustible C&D Materials	Yes	Yes	Yes	Yes	Yes	Yes
Mixed Organics	Yes	Yes	Yes	Yes	Yes	Yes
Mixed MSW	Yes	Yes	Yes	Yes	Yes	Yes
Yard Trimmings	Yes	Yes	Yes	Yes	Yes	Yes
Paper	Yes	Yes	Yes	Yes	Yes	Yes

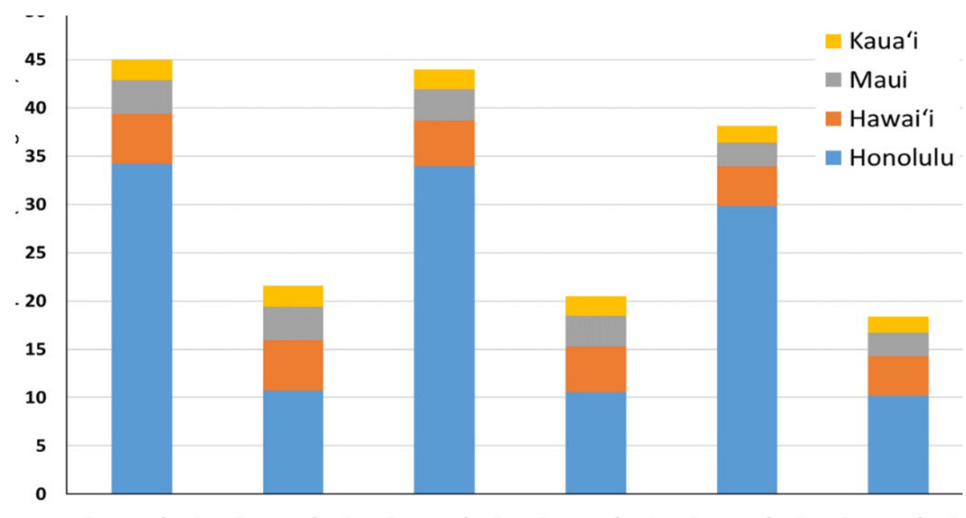


Figure 7. Technical SAF potential from combustible urban waste for six utilization scenarios.

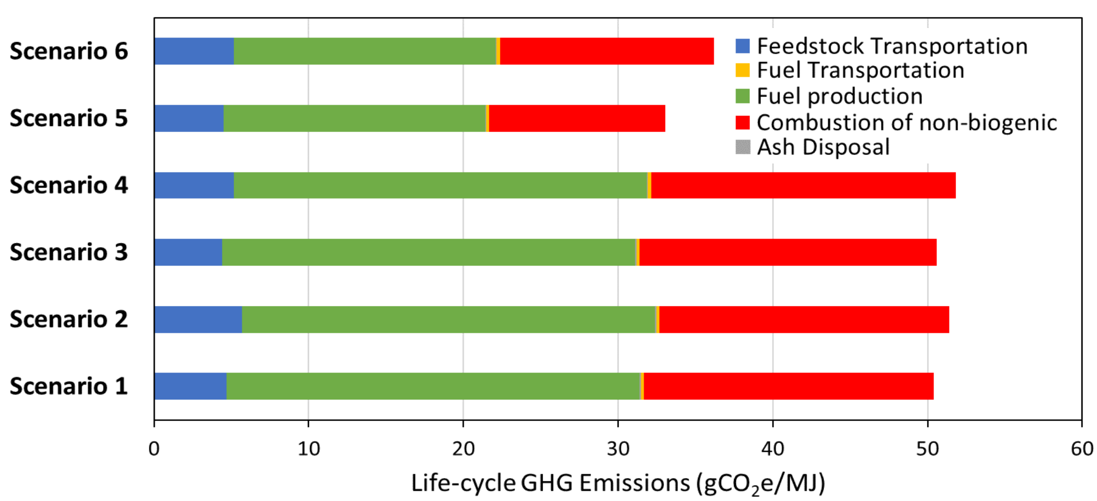


Figure 8. Estimation of GHG emissions from six waste utilization scenarios that include SAF production and combustion in HPOWER.

Biomass: Exploration of Hawai'i Feedstocks

Figure 9 compares land use in 1937, 1980, 2015, and 2020 for the nearly 2 million acres of agricultural lands in Hawaiʻi[2]. 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 Hawaiʻi and Tropical Regions** in the *Energy and Fuels* journal.

The EcoCrop model was used to complete an assessment of plant production requirements to agro-ecological attributes of agricultural lands in the State. Land use constraints included agricultural zoning, land capability classes (an indicator of soil quality), slope, service by irrigation systems, and current agricultural activities. The analysis focused on sites capable of rain-fed production to avoid using irrigated lands that could support food production. Oil seed crops, woody crops, and herbaceous crops were all considered; an example is shown for a eucalyptus species (Figure 10).

The EcoCrop model provides an estimate of each energy crops' productivity across the agricultural landscape. Aggregated yield of biobased feedstock and conversion efficiency from feedstock to final energy product were used as the basis for SAF technical potential estimates under four scenarios:

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

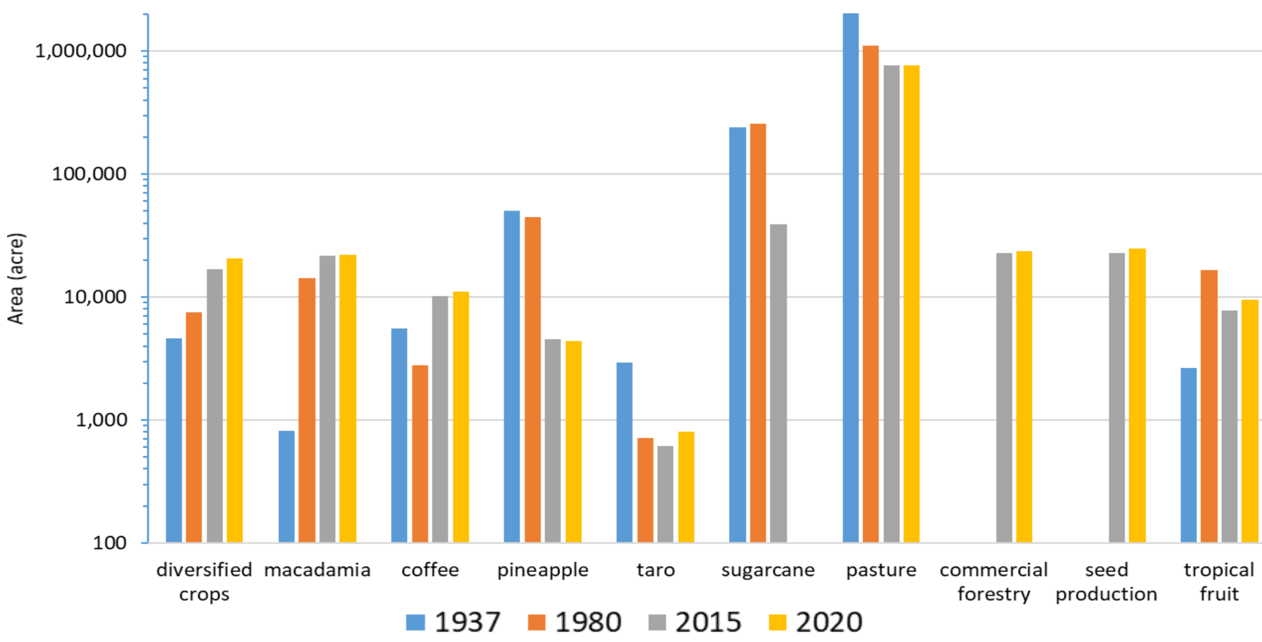


Figure 9. Hawaiʻi agricultural land use patterns, 1937 to 2020[2].

[2] Adapted from data in a) Melrose, J., R. Perroy, S. Cares. 2015. *Statewide agricultural land use baseline 2015*. University of Hawaiʻi at Hilo. Prepared for the Hawaiʻi Department of Agriculture. Honolulu, Hawaiʻi and b) Perroy, R. and E. Collier. 2024. *2020 Update to the Hawai'i statewide agricultural land use baseline*. University of Hawaiʻi at Hilo. Prepared for the Hawaiʻi Department of Agriculture. Honolulu, Hawaiʻi.

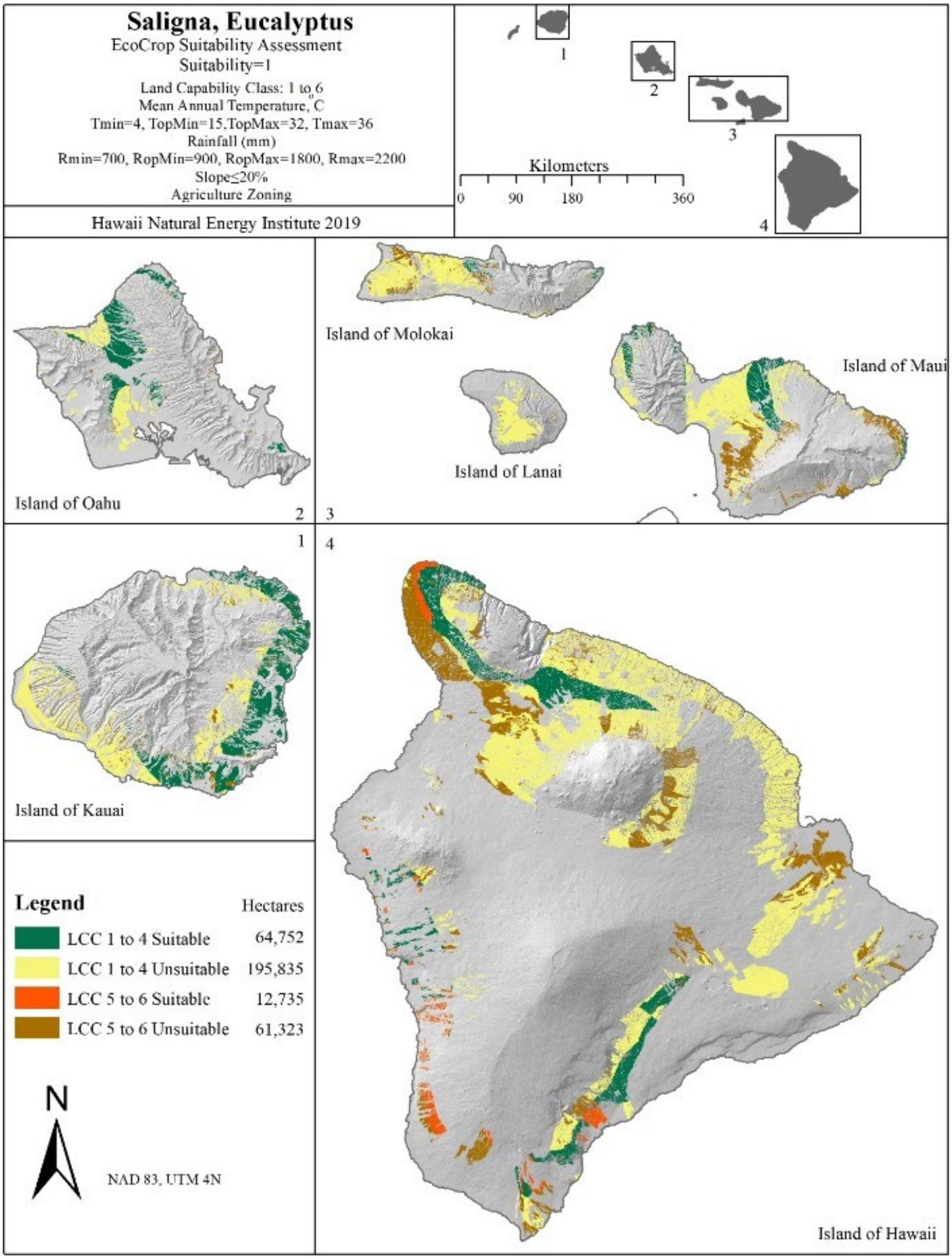


Figure 10. EcoCrop assessment of Saligna, Eucalyptus.

All scenarios assume a EcoCrop suitability index >0.5 on a scale of 0 to 1 using rainfed conditions. Results of the analyses are shown in Figure 11. Note that the results are not mutually exclusive, i.e. the same land area may be included in the estimates of multiple crops. Scenario 1 includes the greatest land area and this is reflected in highest annual SAF production potential estimates, of up to ~100 million gallons. Scenario 2 removes any land serviced by an irrigation system from the analyses, resulting in a reduction in potential to a ~80 million gallons.

Scenario 3 further restricts available lands by excluding those under production identified in a study conducted by the University of Hawaiʻi at Hilo (UH Hilo) for the Hawaiʻi Department of Agriculture[3], resulting in SAF production potential estimates <40 million gallons per year. Scenario 4 considers the dual use of land to support energy crops and pasture by including pasture lands identified in the UH Hilo Baseline report. This results in maximum estimates of ~70 million gallons per year. A report detailing these results is currently being drafted.

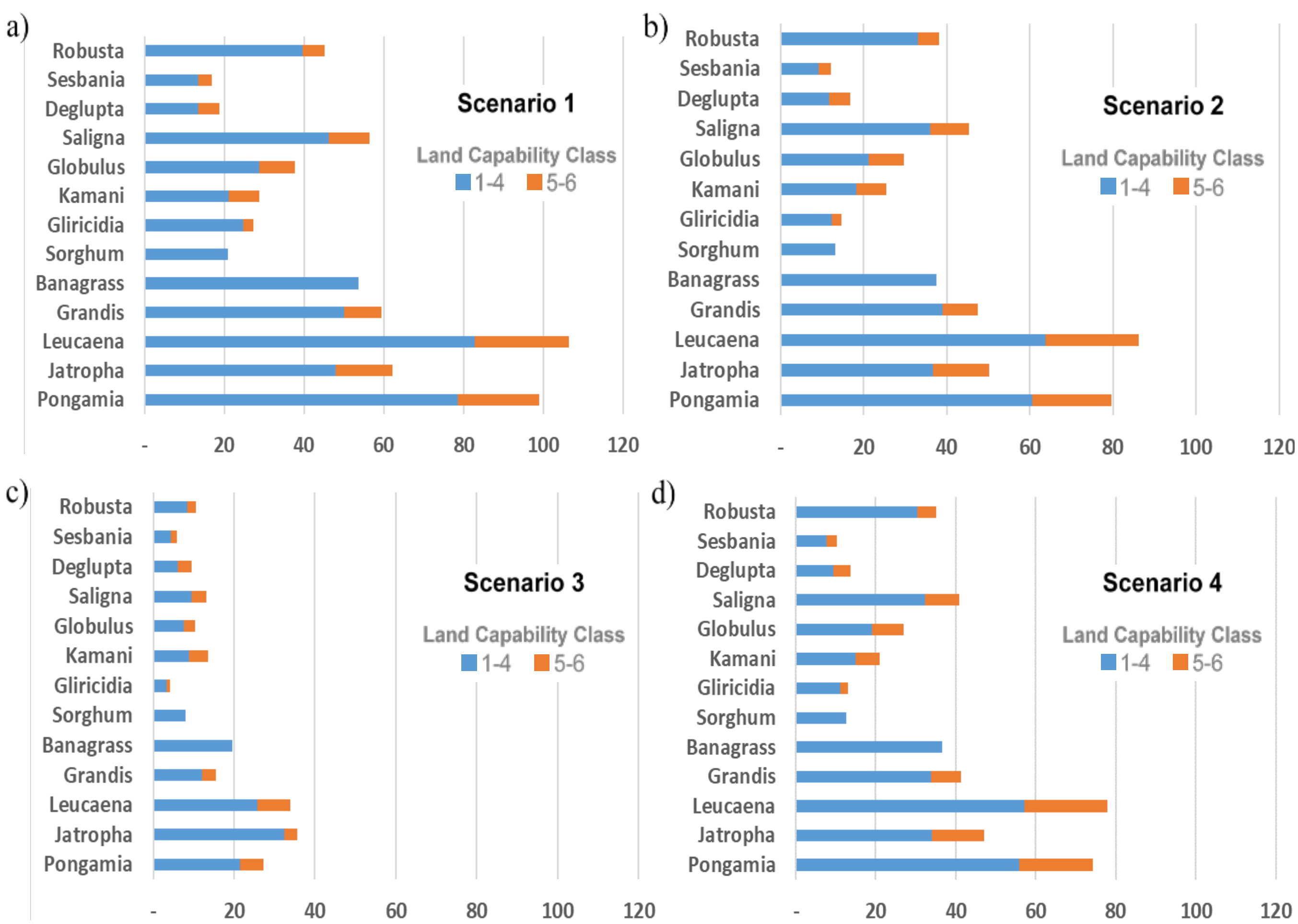


Figure 11. SAF potential (million gallons per year) for 13 energy crop feedstocks under four scenarios: (a) agricultural zoning, slope less than 20%, (b) agricultural zoning, slope less than 20%, excluding land serviced by irrigation systems, (c) agricultural zoning, slope less than 20%, exluding land serviced by irrigation systems and land currently in agricultural use, and (d) agricultural zoning, slope less than 20%, exluding land serviced by irrigation systems and land currently in agricultural use other than pasture. All scenarios assume a EcoCrop suitability index >0.5 on a scale of 0 to 1 using rainfed conditions.

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

Biomass: Pongamia Logistics

EcoCrop energy crop modeling identified pongamia as having the greatest oil production potential based on suitable growing area and yield. The geographic distribution of suitable growing areas across the state provides an opportunity to select pongamia primary processing sites that minimize transportation costs. Seeds in their pods would be harvested and transported to a primary processing location where the seed and pod could be separated – oil could be extracted from the seed, and oil and de-oiled seed cake could be upgraded. Land zoned for industrial use (brownfield site) on each island was considered as potential primary processing sites. Greenfield sites were also considered – identified as land zoned for agriculture with slope less than 5%, and a minimum contigous area of 125 acres. This would accomodate space needed for processing, storage, and possible colocation of complementary industries utilizing the de-oiled seedcake and pod to develop coproducts. A tonne-kilometer value, Tkm_i, was calculated for all i candidate processing locations using Equation 1.

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

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

$$C_{ik} = \left(\frac{Tkm_i - Tkm_{min}}{Tkm_{max} - Tkm_{min}}\right)_k \qquad \text{(Eq. 2)}$$

Where Tkm_{min} and Tkm_{max} are the minimum and maximum Tkm values, respectively, for island k. Candidate sites for Scenario 1, ranked from lowest (C_{ik}=0) to highest (C_{ik}=1) value, are shown in Figures 12 and 13 for brownfield and greenfield locations, respectively.

Figure 14 identifies processing site locations that would minimize transportation requirements for harvested pongamia seed-in-pod from Scenario 4 under constraints of maximum transport distances: 77 km (brown and green), 90 km (pink and tan), and 110 km (blue). As the permissible transportation distance decreases, optimum locations shift from Waimea and Pahala (110 km) to Waimea and Nāʻālehu (90 km), to Kawaihae and Nāʻālehu (77 km). The total *Tkm* value for the two processing site locations are 38.6, 36.2, and 45.0 million ton·km for the 110, 90, and 77 km constraints, respectively, with a marginal concomitant reduction in total amounts of seed-in-pod transported, 1.5 million ton per year. Note that lines in Figure 14 indicate the association between production area (dot) and processing site (star), but the transport distances are based on road network values.

Figure 15 identifies processing sites selected using the same travel distance limits (77, 90, and 110 km) but with an added constraint limiting facility processing capacity to 750,000 tons per year at any given location. Decreasing travel distance limits shifts the locations of the sites that minimize transportation costs. This evaluation would be useful to repeat to site facilities with smaller processing capacities as the first orchards are planted and the total crop harvest is limited.

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

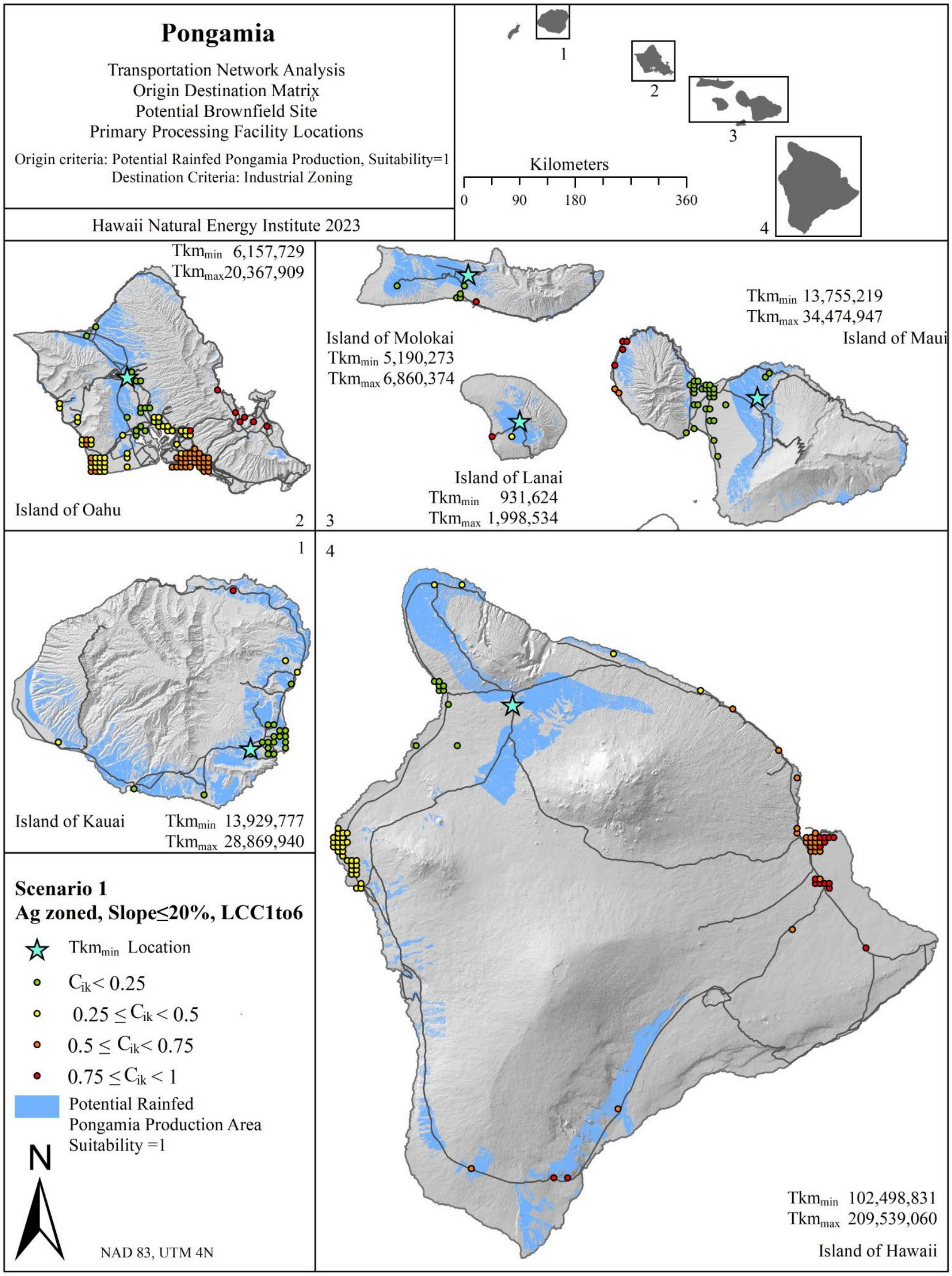


Figure 12. Results of analysis to identify locations to minimize transportation costs of harvested pongamia seed pods to a central brownfield processing site. Blue areas are zoned for agriculture, have slope less than 20%, have land capability class ratings of 1 through 6, and have EcoCrop suitability values of 1.0 for pongamia under rainfed conditions. Potential brownfield processing locations, shown as colored circles, are zoned for industrial use. The star on each island identifies the location of Tkm_{min} corresponding to $C_{ik} = 0$.

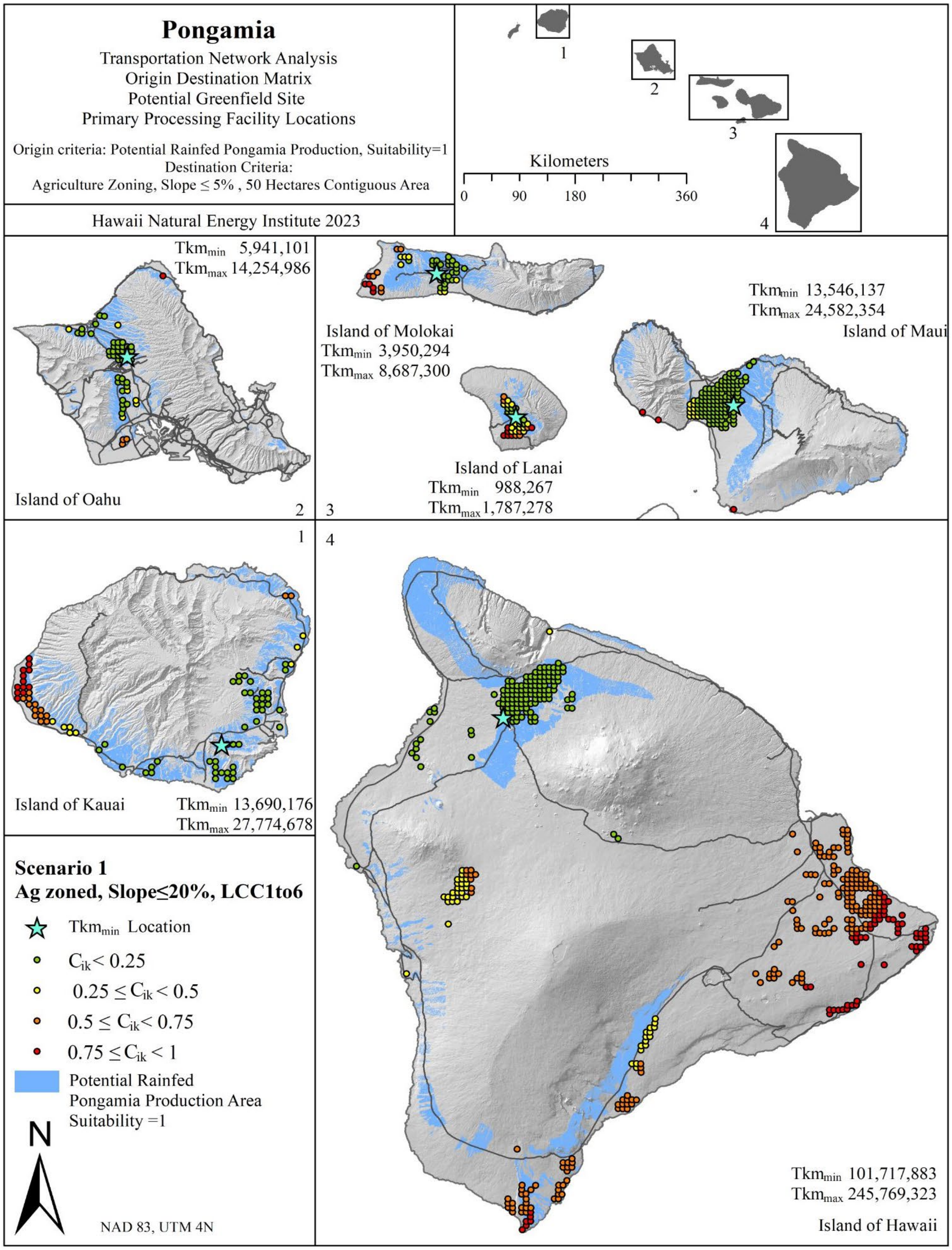


Figure 13. Results of analysis to identify locations to minimize transportation costs of harvested pongamia seed pods to a central greenfield processing site. Blue areas are zoned for agriculture, have slope less than 20%, have land capability class ratings of 1 through 6, and have EcoCrop suitability values of 1.0 for pongamia under rainfed conditions. Potential greenfield processing locations, shown as colored circles, are zoned for agriculture, have slopes ≤5%, and have 125 acres (50 hectares) of contiguous area. The star on each island identifies the location of Tkm_{min} corresponding to $C_{ik} = 0$.

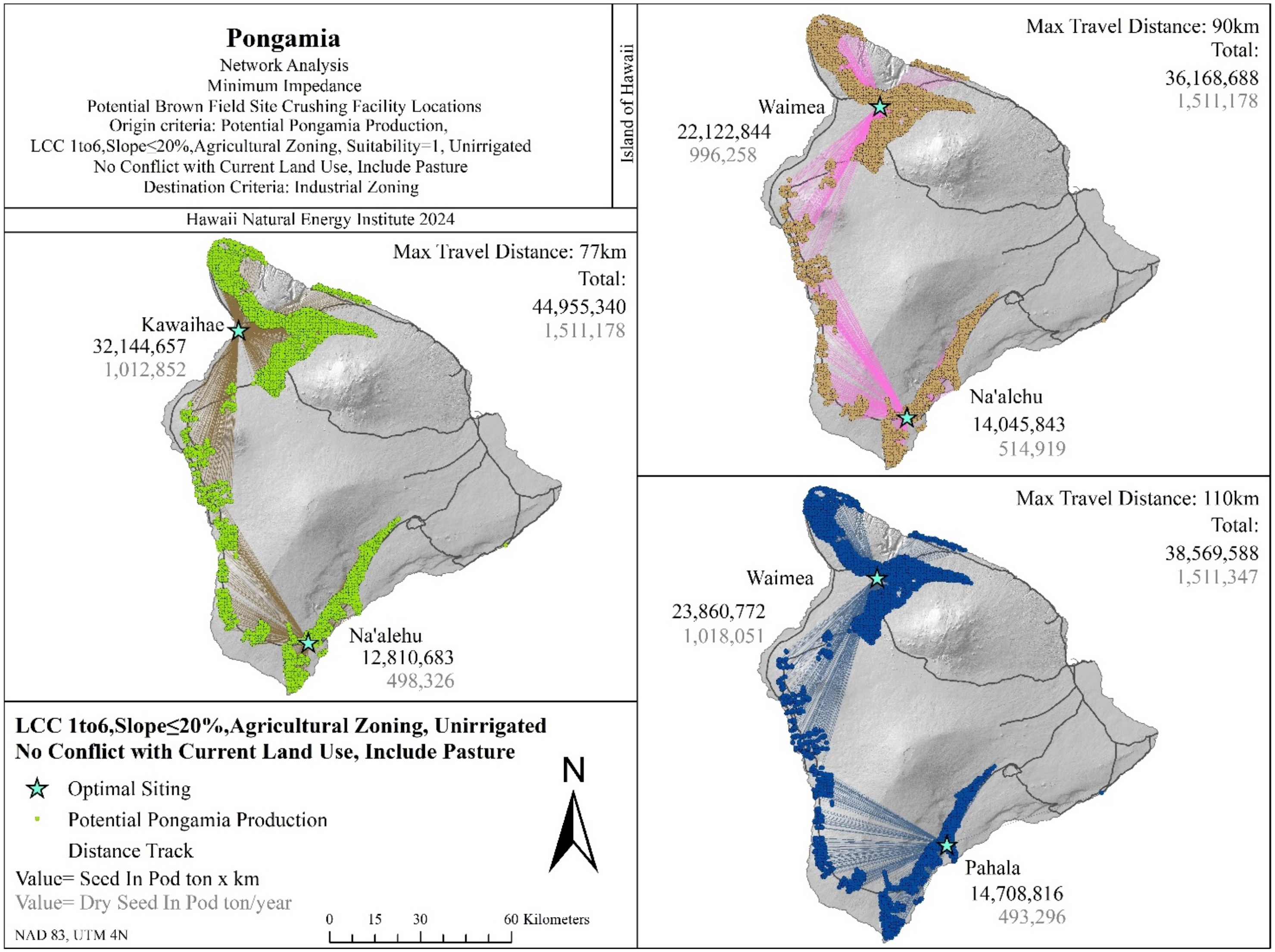


Figure 14. Brownfield processing site locations that would minimize transportation requirements for harvested pongamia seed-in-pod from Scenario 4 under constraints of maximum transport distances: 77 km (brown and green), 90 km (pink and tan), and 110 km (blue). Note that lines indicate the association between production area (dot) and processing site (star), but the transport distances are based on road network values.

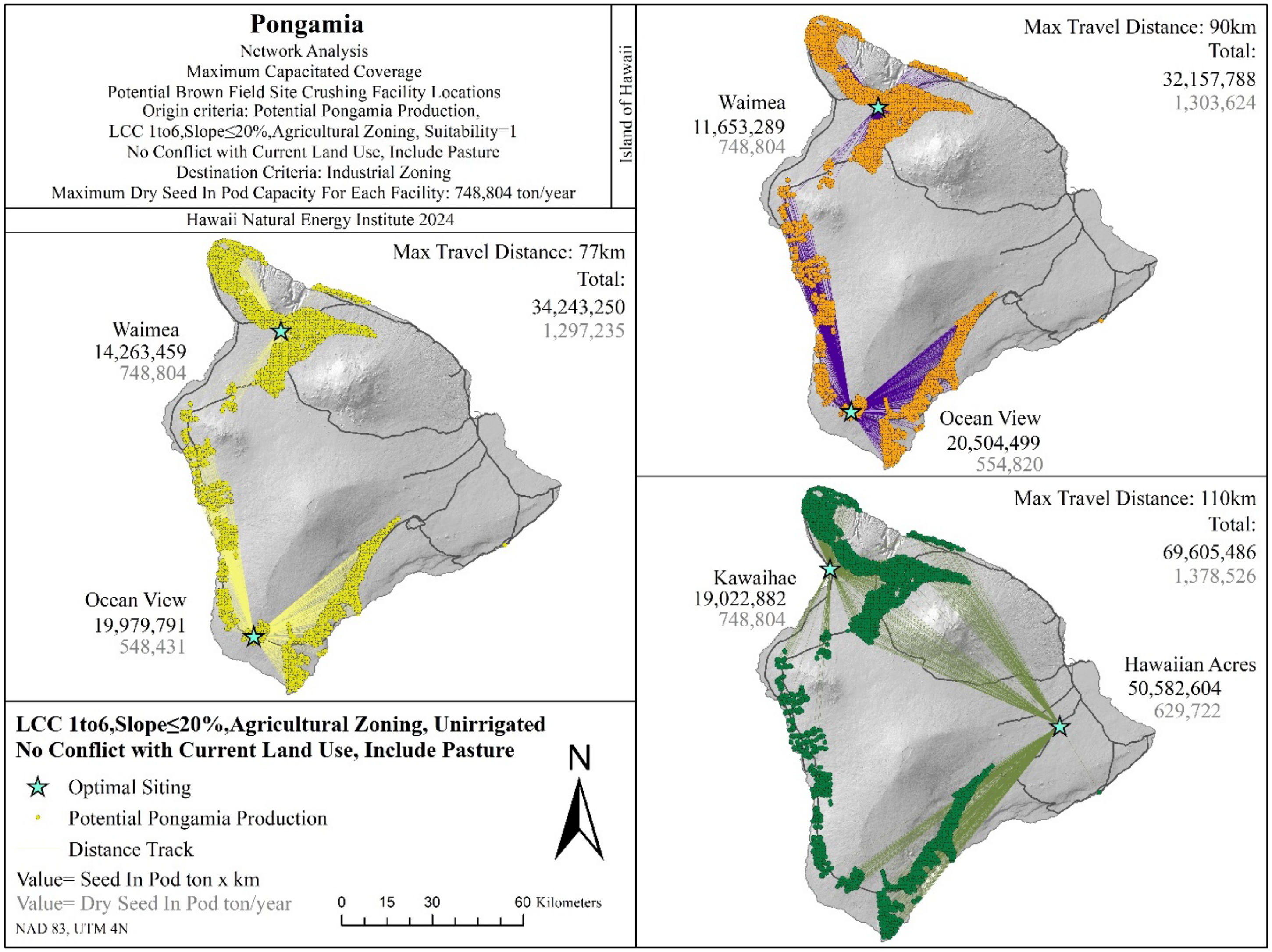


Figure 15. Brownfield processing site locations that would minimize transportation requirements for harvested pongamia seed-in-pod from Scenario 4 under constraints of processing facility capacity <750,000 tons per year and maximum transport distances: 77 km (yellow), 90 km (purple and orange), and 110 km (green). Note that lines indicate the association between production area (dot) and processing site (star), but the transport distances are based on road network values.

Biomass: Evaluation of Pongamia

Of the sustainable aviation fuels currently approved by ASTM and the FAA, those based on the use of oils derived from plants and animals have the highest SAF yield and the lowest production costs. Pongamia (*Millettia pinnata*) (Figure 16) is a tree, native to the tropics, that bears an oil seed and has plantings established on Oʻahu, Maui, and Hawaiʻi island. Pongamia is largely sourced from wild collection in many parts of the world. Pongamia production, processing, and use as an agricultural crop for SAF production would require a value chain (Figure 17). Several projects have been undertaken to provide information needed to develop this value chain. Results are summarized below.

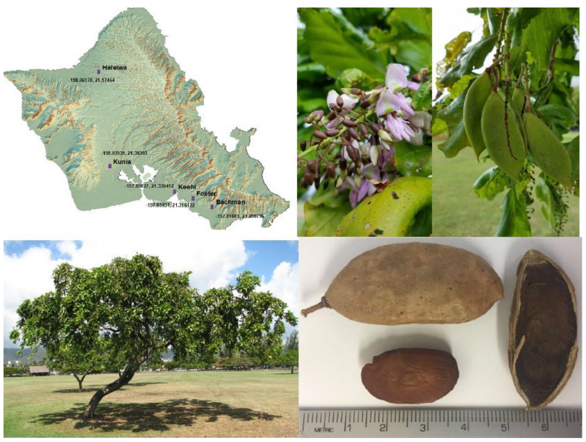


Figure 16. Locations and images of Pongamia.

Economics of Producing Pongamia in Hawaiʻi

Figure 18 proposes common agricultural activities for orchard production of pongamia and illustrates material and energy flows crossing the orchard boundary. Outputs from the orchard include harvested pongamia seed in pod, pongamia trees when the orchard is removed, and land, air, and water emissions. Figure 19 provides additional detail. Growing pongamia trees in Hawaiʻi will require extensive land preparation. In the case of land that has been out of production for several years, preparation may include removal of pre-existing trees, weeds, and debris. Once the soil is prepared, young trees will be purchased and planted. Additional costs may include royalties and grafting costs if specialized cultivars are used. Once the young trees are in the ground, they will need to be pruned, irrigated, and fertilized, and protected from insects and weeds. These cultural costs are higher initially and then decline as the trees mature. When the trees begin producing seed pods, the cost of harvesting will be incurred.

Production costs are evaluated over a 25-year time period. In the first year, the land is prepared at a cost of $265 per acre, then trees are planted at a cost of $3,848 per acre. The newly planted trees are irrigated, pruned, fertilized, and treated for weeds (through mowing and herbicide use) at an initial cost of $600 per acre per year in year 1, rising to $852 per acre in

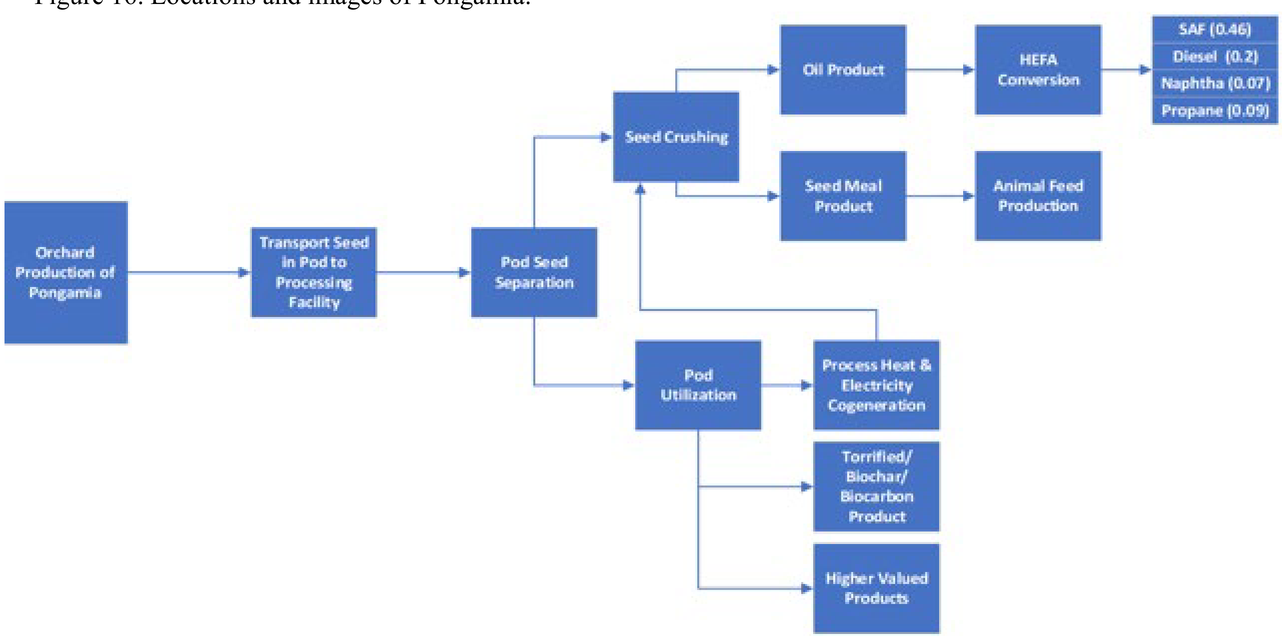


Figure 17. Pongamia value chain from orchard production, aggregation at a processing facility, oil separation, HEFA conversion, and upgrading of byproduct seed meal and fibrous pods.

year 2, $1,014 per acre in year 3, falling to $277 per acre in year 4 and continues to decline gradually reaching $249 by year 25. In year 3, the trees begin flowering and producing seedpods which will be harvested and sold. Initial yields are 0.36 Mg seed (hulled) per acre, peak yields are 3.64 Mg seed (hulled) per acre. Seed yield peaks in year 18 and declines annually through year 25. Baseline production assumptions are displayed in Table 3. Annual seed production is illustrated in Figure 20.

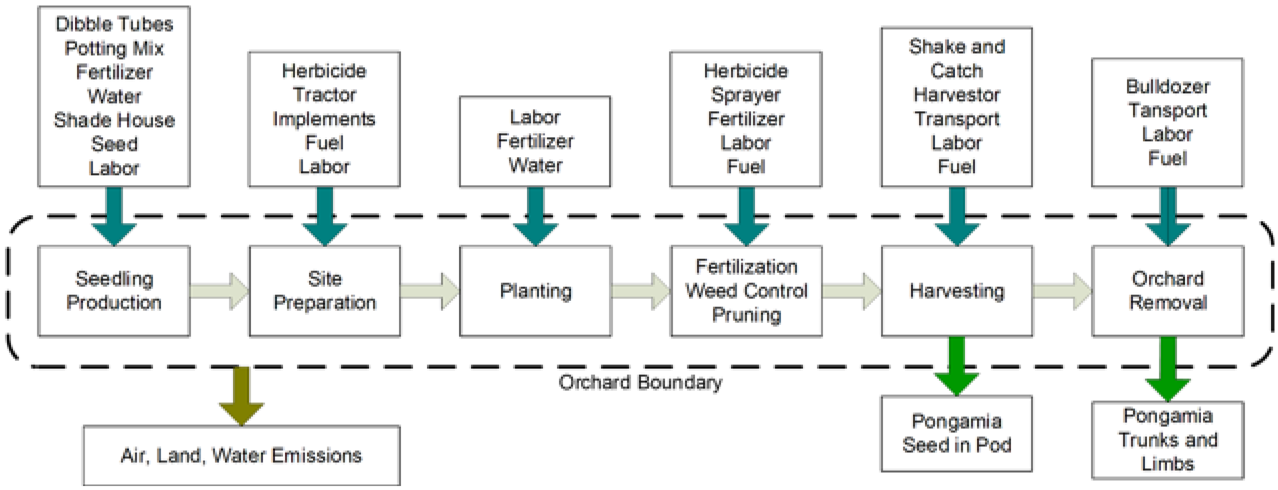


Figure 18. Common agricultural activities propsed for orchard production of pongamia and material and energy flows crossing the orchard boundary.

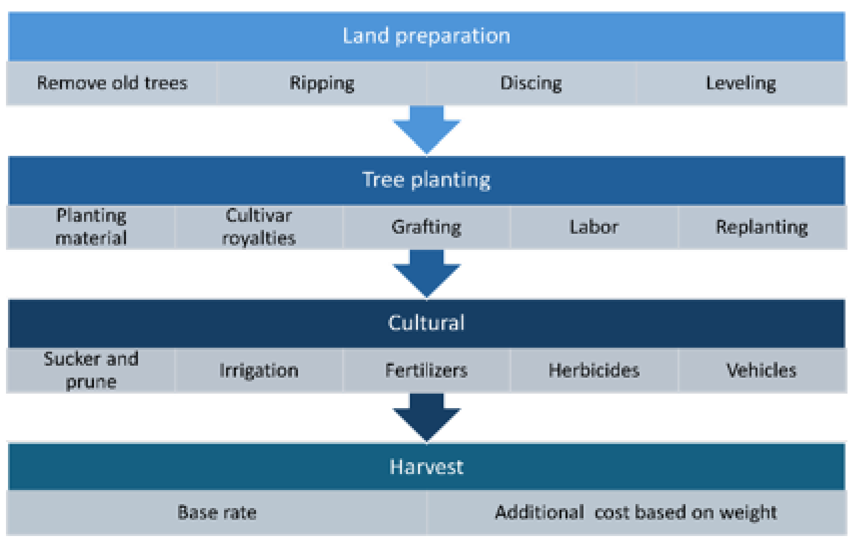


Figure 19. Factors of production proposed for pongamia production systems.

Table 3. Baseline cost assumptions.

Item	Year	Units	Baseline	
Land preparation cost	1	$ per ac	$265	
Tree planting cost	1	$ per ac	$3,848	
			Low	High
Cultural costs (range)	1 to 25	$ per ac	$249	$1,014
Harvest costs (range)	3 to 25	$ per ac	$162	$527
Yield range	3 to 25	Mg seed per ac	0.36	3.64

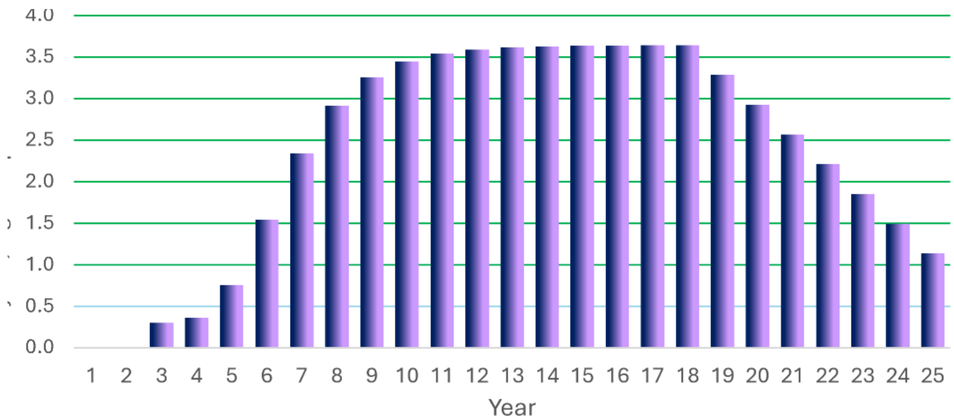


Figure 20. Pongamia seed yield over time in Mg hulled seed per acre per year.

For a one-acre plot of land, results indicate the net revenues will be negative for the first four years of production. In year 5, revenues from the sale of Pongamia seed pods will exceed culture and harvest costs and results in positive net revenues through year 25. With a seed price of $597 per Mg hulled seed, net revenues over 25 years will total $10,522 per acre, not discounted.

Biomass: Pongamia Fuel Properties

Pongamia is a potential resource for renewable fuels in general and sustainable aviation fuel in particular. The physicochemical properties of reproductive material (seeds and pods) from pongamia trees grown in different environments at five locations on O‘ahu were characterized (Figure 21). Proximate and ultimate analyses, heating value, and elemental composition of the seeds, pods, and de-oiled seed cake were determined. The oil content of the seeds and the properties of the oil were determined using American Society for Testing and Materials (ASTM) and American Oil Chemist’s Society (AOCS) methods. The seed oil content ranged from 19 to 33% wt. across the trees and locations. Oleic (C18:1) was the fatty acid present in greatest abundance (47 to 60% wt) and unsaturated fatty acids accounted for 77 to 83% wt of the oil. Pongamia oil was found to have similar characteristics as other plant seed oils (canola and jatropha) and would be expected to be well suited for hydro-processed production of sustainable aviation fuel. These results were published in **Fuel Properties of Pongamia (*Millettia pinnata*) Seeds and Pods Grown in Hawai‘i** in the *ACS Omega* journal.

Figure 21. Pathways from Pongamia seed pods to fuel.

Biomass: Pongamia 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 22). A 2^3 factorial design of the leaching treatment determined the impacts of process operating parameters (i.e. rinse water temperature, rinse duration, and particle size) on the composition and physicochemical properties of the pods and the water. The higher heating value of the pods was found to increase from 16 to 18-19 MJ/kg after leaching, while the ash content was reduced from 6.5% to as low as 2.8% wt, with significant removal of sulfur (S), chlorine (Cl), and potassium (K). The chemical oxygen demand, non-purgeable organic carbon, and total nitrogen of the post-experiment leachates were all found to increase with the rinse water temperature and rinse duration but decrease with the increase of particle size. Leached pods were further processed via torrefaction and the targeted mass and energy yields,

~70% and 85%, respectively, were reached at a process temperature of 270°C. The S, Cl, and K contents of the leached, torrefied pods were found to be lower than that of the raw pods. The reuse of leachate on successive batches of fresh pods showed that ash removal efficiency was reduced after three cycles, although some removal was possible through 15 cycles.

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

Figure 22. Laboratory scale leaching and torrefaction test equipment.

Biomass: Pongamia Invasiveness Assessment
Pongamia (*Millettia pinnata*) is a tree, native to the tropics, which 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, the 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 titled "***Observational Field Assessment of Invasiveness of Pongamia (Millettia pinnata), A Candidate Biofuel Crop in Hawai'i***" summarized this work and is available on HNEI's website.

Biomass: Other Feedstocks
Other potential feedstocks for Hawai'i, kukui (*Aleurites moluccanus*) and kamani (*Calophyllum inophyllum*) nut oils, were also explored. The oil content of the kukui nuts is ~60% wt, which is ~20-30% wt higher than that of pongamia seeds and kamani nuts. The unsaturated fatty acids, however, accounted for ~90 % wt of the kukui nut oil, slightly higher than that of kamani nut (~75% wt) and pongamia seed oil. Kukui and kamani nut oil are different from the pongamia seed oil, in that the primary fatty acid is linoleic acid (C18:2). The results of the study conducted on kukui were published in **Comprehensive Characterization of Kukui Nuts as Feedstock for Energy Production in Hawai'i** in the *ACS Omega* journal.

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

Contact: Scott Turn, sturn@hawaii.edu

Last Updated: November 2024

D2: Advanced Fuel Characterization and Development

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

New analytical methods under development can 1) evaluate the composition of fuels currently in use and those stored as strategic reserves and 2) investigate the impacts of crucial nitrogen and sulfur containing compounds and additives on fuel properties. Comprehensive fuel composition information can be further employed to replace costly experimental measurements by calculating various physicochemical properties of conventional petroleum and alternative fuels. The knowledge gained in this project will enhance our understanding of how HOS and fuel additives impact fuel stability and physicochemical properties, guide efforts to preserve fuel quality, reduce the cost of fuel characterization, and advance the development of alternative HED fuels.

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

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

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

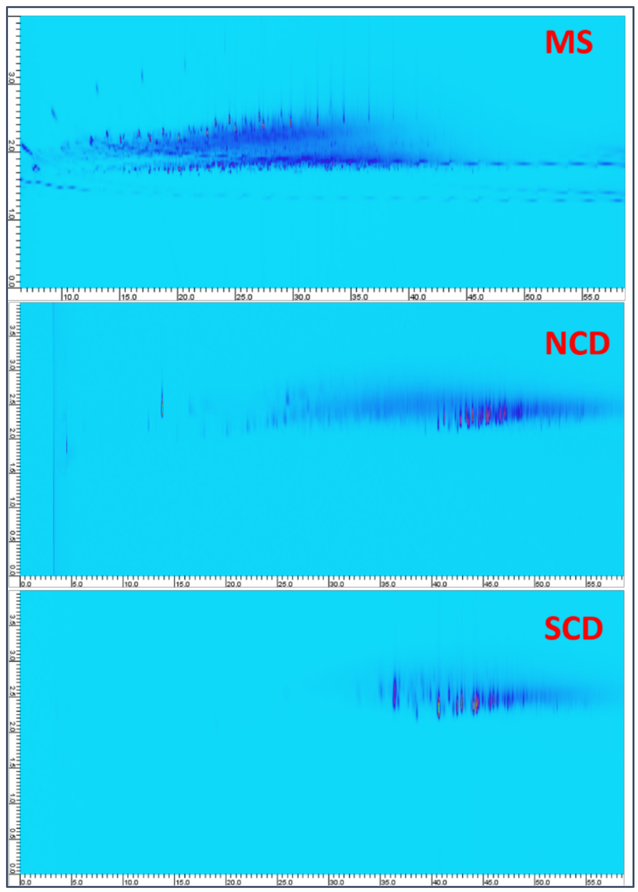


Figure 1. Comprehensive 2D-GC analysis of F-76 diesel fuel with MS, NCD, and SCD.

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

2D-GC applications for sulfur-containing compounds (SCCs) analysis.

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

Currently, HNEI's activities include:

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

To date, this project has produced the following publications:

- 2025, J. Fu and S.Q. Turn, **Oxidation mechanism of sulfur-containing compounds and antioxidant depletion dynamics: Insights into interactions**, *Fuel*, Vol. 381, Part A, Paper 133341. (Open Access: **PDF**)
- 2023, J. Fu, P.K. Le, and S.Q. Turn, **Impacts of antioxidants on stability of biodiesel derived from waste frying oil,** *Biofuels, Bioproducts and Biorefining*, Vol. 17, Issue 6, pp. 1496-501.
- 2023, J. Fu, **Dissolved water in jet fuels: a low-temperature quality and water solubility study**, *Fuel*, Vol. 331, Part 2, 1 Paper 125950. (Open Access: **PDF**)

Funding Source: Office of Naval Research

Contact: Scott Turn, sturn@hawaii.edu;

Last Updated: November 2024

D3: Novel Biocarbons

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

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

PROJECT STATUS/RESULTS: Research at HNEI has identified certain constant-volume/pressurized reaction conditions that result in the formation of biochar with drastically altered morphology compared to the parent biomass. This unique biochar experiences a transient plastic phase (TPP) during carbonization, representing a new biomass carbonization pathway. The underlying mechanisms of TPP formation and utility are still being explored.

The current research effort used parametric research design to independently study the effects of pressure, temperature, water content, and biomass type on the formation of TPP biochar. In addition to standard analytical tools (proximate analysis, true density, ultimate analysis), powder compaction experiments have been developed to characterize material plasticity and mechanical strength. These fundamental insights have been leveraged to increase biocarbon mechanical strength, a critical bottleneck for commercial applications.

Experimental results demonstrate that TPP formation proceeds through a molten phase. Elevated pressure serves to keep water in the condensed phase, inhibiting condensation reactions and enabling molten phase formation. TPP formation conditions were identified for a range of biomass types including hardwoods, softwoods, and herbaceous materials.

Results from powder compaction experiments show that TPP biochar has increased plasticity along with a reduced glass transition temperature. Experiments comparing the mechanical strength of TPP and standard biocarbon materials show the TPP material is 10 times stronger, and twice as dense. Efforts to maximize the mechanical strength of TPP biocarbon achieved another 10x improvement, the strongest biocarbon material reported in the scientific literature (Figure 1). These mechanical properties exceed values required for numerous industrial applications.

This novel production pathway overcomes technical barriers limiting biomass utilization as feedstock for biocarbons that can displace fossil carbon products. Potential applications include metallurgical reductants, binders, electrodes, or high value specialty materials. A patent application has been filed to protect this intellectual property and licensing opportunities are available.

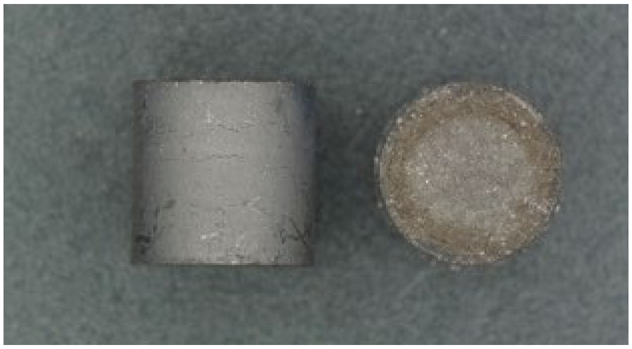


Figure 1. Biocarbon pellets produced from TPP biochar.

To date, this project has produced the following publications:

- 2024, K. Castillo, R.L. Johnson, C. Castillo, L. Wang, Ø. Skreiberg, and S.Q. Turn,

Experimental optimization of pellet tensile strength from spruce biochar produced at elevated pressure, *Energy & Fuels*. In review.

- 2024, B. Babinszki, I.S. Czirok, R. Johnson, Z. Sebestyén, E. Jakab, L. Wang, S. Turn, Ø. Skreiberg, and Z. Czégény, **Volatile matter characterization of birch biochar produced under pressurized conditions**, *Journal of Thermal Analysis and Calorimetry*, Vol. 149, pp. 10915-10926. (Open Access: **PDF**)
- 2023, R.L. Johnson, K. Castillo, C. Castillo, C. Hihara, Q.V. Bach, L. Wang, Ø. Skreiberg, and S.Q. Turn, **Biocarbon production via plasticized biochar: role of feedstock, water content, catalysts, and reaction time,** *Energy & Fuels*, Vol. 37, Issue 20, pp. 15808-15821.
- 2023, R.L. Johnson, K. Castillo, C. Castillo, L. Wang, Ø. Skreiberg, and S.Q. Turn, **Use of plasticized biochar intermediate for producing biocarbons with improved mechanical properties,** *ACS Sustainable Chemistry & Engineering*, Vol. 11, Issue 15, pp. 5845-5857.

Funding Source: SINTEF Energy Research; Office of Naval Research

Contact: Scott Turn, sturn@hawaii.edu;
Robert Johnson, robertlj@hawaii.edu

Last Updated: November 2024

<u>Objective and Significance</u>: The objective of this research is to improve the durability and efficiency of *chalcopyrite* and *perovskite* thin-film photo-absorbers for photoelectrochemical (PEC) production of *solar fuels*, to reduce the production cost of renewable hydrogen.

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

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

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

<u>Project Status/Results</u>: In 2023, HNEI and its partners at Stanford, UNLV, LLNL and NREL received DOE funding to specifically develop a novel integration scheme in which material classes can be combined regardless of their nature while preserving their intrinsic performance. Such a scheme, pioneered by HNEI and known as *semi-monolithic* integration, relies on 2D materials-assisted exfoliation and room temperature bonding techniques to transfer fully integrated cells from their original substrates onto new handles.

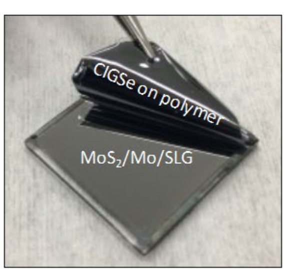
With this integration scheme, sub-cells can be successively transferred onto a new host to create a fully functional MJ structure. By design, semi-monolithic integration allows to circumvent all material incompatibilities, enabling new MJ architectures otherwise not possible with conventional monolithic integration. With this integration scheme, HNEI was able to fabricate the world's first *chalcopyrite* triple junction PEC device with 3% STH efficiency (proof-of-concept). HNEI also leveraged this new technology to combine *chalcopyrites* and *perovskites* photo-absorbers in MJ devices with STH efficiencies of 11%.

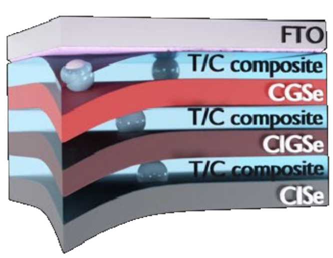
To date, this research has produced the publications and presentations linked on the following page.

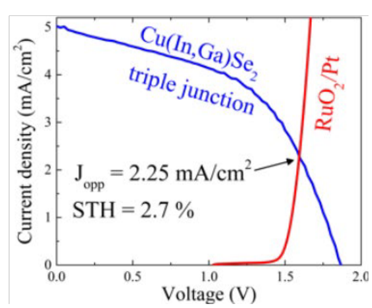
Funding Source: Department of Energy

Contact: Nicolas Gaillard, ngaillar@hawaii.edu

Last Updated: November 2024







ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

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

PRESENTATIONS:

1. 2024, N. Gaillard, **Semi-Monolithic Integration of Dissimilar Material Classes into Efficient Water Splitting Devices**, Presented at the Electrochemical Society PRiME Meeting, October 6-11, Honolulu, Hawaiʻi, Symposium L04, Abstract 3947.
2. 2024, K. Outlaw-Spruell, C. Muzzillo, K. Zhu, N. Gaillard, **Semi-Monolithic Multijunction Devices for Unassisted Photoelectrochemical Water Splitting**, Presented at the Electrochemical Society PRiME Meeting, October 6-11, Honolulu, Hawaiʻi, Symposium L04, Abstract 3932.
3. 2024, N. Gaillard, **Semi-Monolithically Integrated Photoelectrochemical Devices for Unassisted Water Splitting**, Presented at the 245th Electrochemical Society Meeting, May 26-30, San Francisco, California, Symposium I02, Abstract 1990.
4. 2024, K. Outlaw-Spruell, C. Muzzillo, K. Zhu, N. Gaillard, **Anisotropic Conductive Adhesive for Semi-Monolithic Integration of Multi-Junction PV and PEC Devices**, Presented at the Materials Research Society Spring Meeting, April 22-26, Seattle, Washington, Symposium EN05.07.04.

Hawaiʻi Natural Energy Institute Research Highlights

Appendix D: Alternative Fuels

D5: NELHA and MTA Hydrogen Stations and Fuel Cell Electric Buses

<u>Objective and Significance</u>: In 2022, HNEI commissioned a 65kg/day hydrogen production and dispensing station on the Island of Hawaiʻi at the Natural Energy Laboratory Hawaiʻi Authority (NELHA) (Figure 1) and demonstrated on-site fueling of an electric-fuel cell hybrid bus. The overall objective of the project is to evaluate the technical and financial performance and durability of the equipment, and support a fleet of three hydrogen Fuel Cell Electric Buses (FCEB) operated by the County of Hawaiʻi Mass Transit Agency (MTA). The knowledge gained in this project will inform the MTA on benefits and issues associated with transitioning from a diesel bus fleet to a zero emissions FCEB fleet in support of the County of Hawaiʻi's clean transportation goals. The knowledge will also help inform decisions on other islands.

Figure 1. HNEI's NELHA hydrogen station.

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

Figure 2. Concept of hydrogen transport.

<u>Project Status/Results</u>:

Hydrogen System: The NELHA hydrogen fueling station (Figure 3) was commissioned in 2021. The first fill of a hydrogen bus for public transportation took place on March 24, 2022.

Figure 3. HNEI's NELHA hydrogen station.

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

Figure 4. HydroPac compressor.

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

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

Figure 5. Hydrogen transport trailer.

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

Figure 6. Hydrogen station dispenser.

The fueling dispensers located at NELHA and at MTA are identical except for the addition of a boost compressor at the MTA site integrated into the MTA fueling post (Figure 7). The boost compressor system was developed 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.

The Hele-On 21-passenger FCEB (Bus #111) (Figure 8) was purchased with funds from the Energy Systems Development Special Fund. This bus, manufactured by Eldorado National, and converted to a hydrogen-electric drive train by U.S. Hybrid, is ADA-compliant. Within the last year, the fuel cell power system was upgraded by replacing the original 30 kW Hydrogenics fuel cell with a new state-of-the-art 40 kW U.S. Hybrid fuel cell. Data on bus and fuel cell performance has been collected and is being analyzed.

Figure 8. Hele-On 21-passenger FCEB.

Onboard hydrogen is stored in composite carbon fiber cylinders located under the bus with a capacity of 19 kg. The fuel cell power system is integrated with two 11 kWh (total 22 kWh) LG Lithium-ion battery packs to provide motive power to a 200 kW electric drive system. 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.

Figure 9. Bus export power unit.

In additon to the Hele-on 21 passenger bus, two 19-passenger FCEBs (Figure 10) were acquired by the MTA from Hawai‘i Volanoes National Park

(HAVO). These buses were converted by U.S. Hybrid and are of similar design to the 21-passenger FCEB. Onboard hydrogen capacity is 10 kg giving a projected range of 100 miles. These buses are being upgraded with 90 kW Hyundai fuel cells and one 33 kWh A123 Lithium-ion battery using funding provided by the County of Hawaiʻi.

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 at Volcanoes National Park.

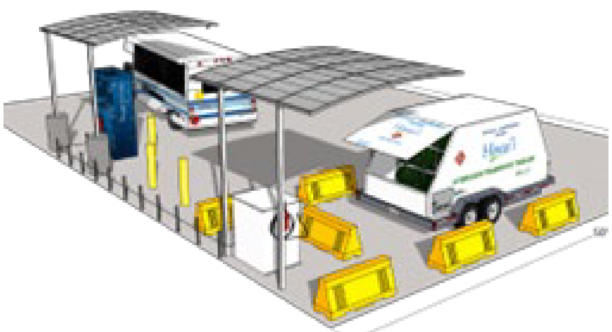


Figure 11. Concept design of MTA fueling dispensing station.

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

Table 1. NELHA Hydrogen Station Observed Power Usage.

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

MTA FCEB Performance: The MTA buses are fitted with sensors and a data acquisition system that monitors bus system performance. Data is transmitted by cell phone telemetry to a remote computer. Outputs include powertrain energy consumption in kWh per mile and miles per kg of hydrogen. This data supports management of the bus fleet including identifying developing maintenance problems. The first bus (#111) travelled a total of 6,471 miles under fuel cell power.

This project has produced the following papers:

- 2020, A. Headley, et al., **Valuation and cost reduction of behind-the-meter hydrogen production in Hawaiʻi**, MRS Energy & Sustainability, Vol. 7, Paper E26.
- 2020, M. Virji, et al., **Analyses of hydrogen energy system as a grid management tool for the Hawaiian Isles**, International Journal of Hydrogen Energy, Vol. 45, Issue 15, pp. 8052-8066.

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

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

Last Updated: November 2024

Appendix E: Electrochemical Power Systems

E1: Contaminant Tolerant Fuel Cells for Harsh Environments

OBJECTIVE AND SIGNIFICANCE: Fuel cells offer the opportunity to significantly increase the flight duration of electric powered unmanned aerial vehicles (UAVs). With fuel cell power systems, increases of 5-10x in flight duration are possible for the same volume and weight constraints as high energy lithium batteries. Under this task, HNEI continued support to the Naval Research Laboratory's (NRL) efforts to develop lightweight, high efficiency fuel cell systems for UAVs including developing components that enhance contaminant tolerance. Contamination mechanisms in proton exchange membrane (PEM) fuel cells can become quite complex with many sources (air, fuel, system materials) and problems can be compounded by the contaminant reaction products that impact many key fuel cell materials.

BACKGROUND: A partnership between HNEI and NRL was established in 2009 to aid in NRL's development of the IonTiger UAV using a fuel cell made by an outside vendor. This NRL program resulted in an unofficial world-record fuel cell powered UAV flight of 26 hours on compressed hydrogen, and later 48 hours using an NRL-developed, cryogenic hydrogen storage system. Subsequently, NRL has continued to develop their own proprietary fuel cells and systems for UAV applications. HNEI has supported this effort, and continues to support this effort, via diagnostic testing, evaluation of needs, and design recommendations.

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

PROJECT STATUS/RESULTS: Under this work, HNEI has established a fabrication system (Figure 1) originally 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 improved 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.

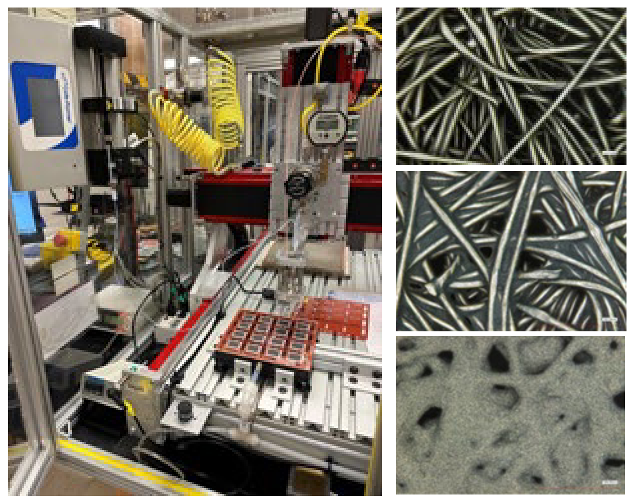


Figure 1. Upgraded spray coating system (left) for producing new HTPEM electrodes and laser confocal scans showing variety of depositions performed (right, top) bare carbon paper (right, middle) PTFE deposition (right, bottom) catalyst layer deposition.

To date, we have established a multi-electrode fabrication approach to produce up to 16 electrodes in one deposition run. HNEI also initiated performance evaluations of in-house fabricated electrodes and began planning for in-situ contaminant tolerance evaluations to be initiated in early 2025.

This work has resulted in the publications and presentations listed on the following page.

Funding Source: Office of Naval Research

Contact: Keith Bethune, bethune@hawaii.edu

Last Updated: November 2024

<u>ADDITIONAL PROJECT RELATED LINKS</u>

PAPERS AND PROCEEDINGS:

1. 2020, K. Bethune, J. St-Pierre, J.M. LaManna, D.S. Hussey, and D.L. Jacobson, **Contamination Mechanisms of Proton Exchange Membrane Fuel Cells-Mass Transfer Overpotential Origin**, The Journal of Physical Chemistry C, Vol.124, Issue 44, pp. 24052-24065.
2. 2020, Y. Garsany, C.H. Bancroft, R.W. Atkinson III, K. Bethune, B.D. Gould, K.E. Swider-Lyons, **Effect of GDM Pairing on PEMFC Performance in Flow-Through and Dead-Ended Anode Mode**, Molecules, Vol. 25, Issue 6, Paper 1469. (Open Access: **PDF**)
3. 2015, B.D. Gould, J.A. Rodgers, M. Schuette, K. Bethune, S. Louis, R. Rocheleau, K. Swider-Lyons, **Performance and Limitations of 3D-Printed Bipolar Plates in Fuel Cells**, ECS Journal of Solid State Science and Technology, Vol. 4, Issue 4, pp. P3063-P3068. (Open Access: **PDF**)

PRESENTATIONS:

1. 2022, Y. Garsany, R. E. Carter, M.B. Sassin, K. Bethune, and B. Gould, **Pairing Gas Diffusion Media for High-Power PEMFC Operation,** Presented at the ECS 2022-02 Meeting, Atlanta, Georgia, October 9-13, Abstract 1380.
2. 2020, Y. Garsany, C.H. Bancroft, R.W. Atkinson, K. Bethune, B.D. Gould, K. Swider-Lyons, **Operation of PEMFC Anodes in Dead-Ended Vs. Flow-through Modes**, Presented at the ECS 2020-02 Meeting, Honolulu, Hawai‘i, October 4-9, Abstract 2212.
3. 2019, Y. Garsany, R.W. Atkinson, K. Bethune, J. St-Pierre, B.D. Gould, K. Swider-Lyons, **Cathode Catalyst Layer Design with Graded Porous Structure for Proton Exchange Membrane Fuel Cells**, Presented at the ECS 2019-02 Meeting, Atlanta, Georgia, October 13-17, Abstract 1423.

E2: Anion Exchange Membrane Fuel Cell

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

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

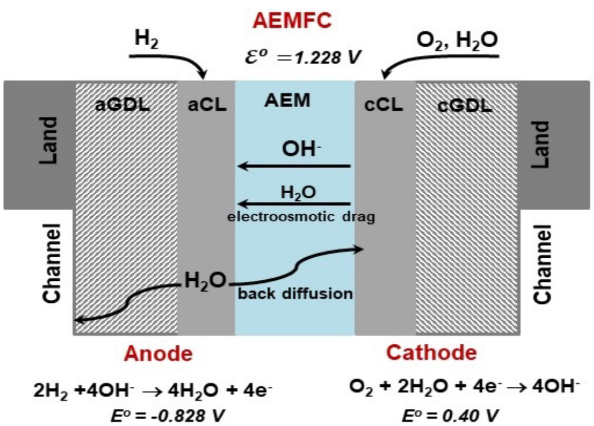


Figure 1. Schematic representation of AEMFC.

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

The main approach to improve AEMFC performance and durability is to design catalyst layers with optimal porosity, hydroxide ion conductivity and thickness to ensure development of three phase boundaries, and sufficient reagents transport, as well as adequate choice of gas diffusion layers (GDLs) for better water management. In addition, there is a lack of harmonized testing protocols and procedures, and development of electrochemical diagnostics and approaches are critical for AEMFC.

Project Status/Results: Under this effort, HNEI has achieved the following results. To address the observed performance discrepancy in AEMFCs, suppliers of anion exchange membranes and ionomers were consulted to discuss potential causes. Based on these discussions, it was recommended to re-evaluate the conditions for ink formulation, preparation, and deposition to ensure consistency and optimal performance. For electrode production, it was suggested to deposit the catalyst ink onto a heated substrate or membrane (T=40-50°C). Following these recommendations, several series of MEAs were manufactured, utilizing Pt/C on both electrodes and PtRu/C and Pt/C for the anode and cathode, respectively. The effects of compression ratio on the integrity of membrane electrode assemblies (MEAs) were studied, revealing an optimal compression range of 20-25%. Based on these findings, recommendations were developed for selecting suitable gasket materials to maintain MEA durability and performance. An evaluation of MEAs with Pt and PtRu anode electrodes demonstrated that the use of PtRu significantly improved MEA performance (Figure 2).

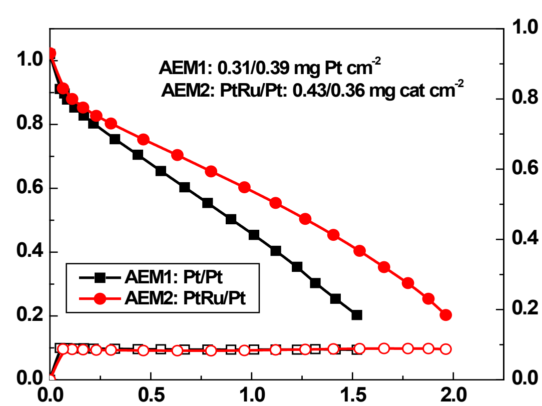


Figure 2. Polarization curves and high frequency resistance (HFR) for Pt and PtRu AEMFCs.

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

Funding Source: Office of Naval Research

Contact: Tatyana Reshetenko, tatyanar@hawaii.edu

Last Updated: November 2024

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

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

PROJECT STATUS/RESULTS: This work is exploring a simple and environmentally friendly synthesis process for carbides that involve in situ carburization of a metal precursor and a carbon material. Considering the excellent electrochemical stability of TiC, the commercially available TiC was chosen as the carbon source and support to increase the stability of carbides. SEM/EDS was used for catalysts morphological and elemental analysis. SEM images revealed the existence of nanoflakes in vanadium carbides and composite oxides (Figure 1). EDS elemental mapping indicated the presence of carbon (C) and vanadium (V) (Figure 1). The thermal stability of carbides and composite oxides in air was conducted using thermogravimetric analysis (TGA).

As shown in Figure 2, TGA results indicated that vanadium carbides and titanium vanadium composite oxides had good thermal stability and oxidation resistance up to 350 and 450°C in air, respectively. Both carbides and carbon supports exhibited increased hydrogen evolution reaction (HER) catalytic activity after up to 1.4 V cycling verified by two types of counter electrodes (i.e., Pt and graphite rod).

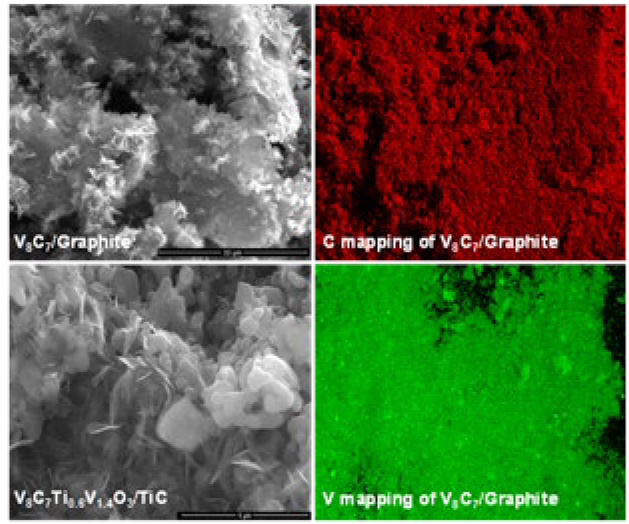


Figure 1. SEM images and EDS elemental mappings.

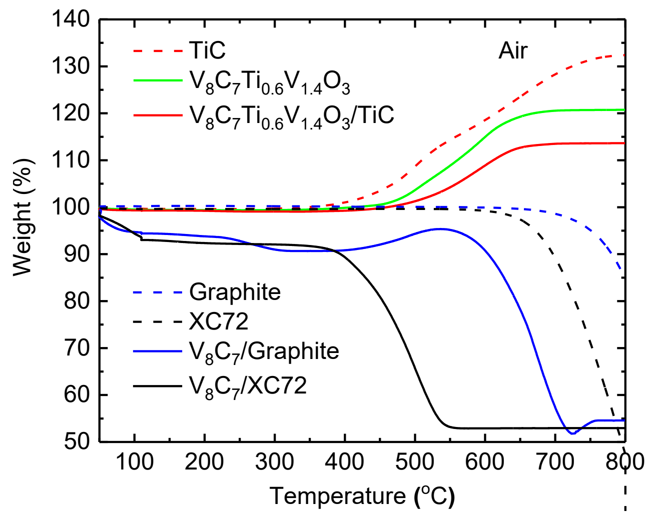


Figure 2. Thermogravimetric curves in air.

Funding Source: Office of Naval Research

Contact: Jing Qi, qijing@hawaii.edu

Last Updated: November 2024

E4: Materials Enablers for Advanced Manufacturing of Attritable Fuel Cells

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

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

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

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

PROJECT STATUS/RESULTS: Under this work, HNEI is investigating simpler system architectures to enable reduced cost of construction for high temperature proton exchange membrane fuel cells (HT-PEM). The use of HT-PEM also has the potential to reduce the costs of precious metal catalysts and polymer membrane substrates, further supporting the lower cost targets. The higher operating temperatures of HT-PEM (120-200°C) directly address heat rejection challenges. Volumetric storage challenges of hydrogen are indirectly addressed in this project through a simpler fuel cell system architecture and increased heat rejection that leads to volume savings in the fuel cell system that can be applied to hydrogen storage space claim.

To date, HNEI has successfully demonstrated the use of flexible PCB based materials for planar current collection in a single cell without any performance loss vs standard configurations. Fabrication of 2-cell prototype (Figure 1) has also begun. In 2024, ONR awarded a three year program extension to continue this work.

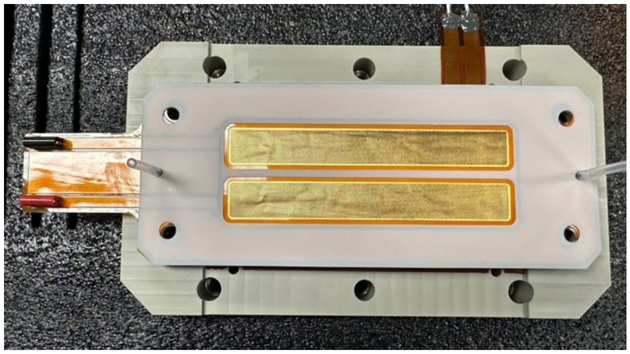


Figure 1. 2-cell prototype fuel cell using 1 cm x 10 cm electrodes with planar current collection assembly in progress. Clearly visible are the flexible PCB based-current collectors.

Results of this work has been presented at the Electrochemical Society meetings in 2023 and 2024: ***Investigating the Suitability of Printed Circuit Components for Fuel Cells*** and ***Investigating the Suitability of Printing Metal Current Collectors Directly Onto the GDMs of PEMFCs***.

Funding Source: Office of Naval Research

Contact: Keith Bethune, bethune@hawaii.edu

Last Updated: November 2024

E5: 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 in the cathode catalyst layer of high temperature proton exchange membrane fuel cell (HT-PEMFC) to overcome the phosphoric acid (H_3PO_4) leaching issue. Operation of PEMFCs at HTs would facilitate meeting U.S. Department of Energy's (DOE) technical targets for performance, power and energy density, cost, and liability by inhibiting the poisoning effects of air pollutants and fuel impurities and simplifying the system's water and heat management.

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

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

PROJECT STATUS/RESULTS: At HNEI, novel inorganic layered structure materils are being developed as proton conducting electrolyte. The materials will be integrated into the in the cathode catalyst layer of HT-MEAs to overcome H_3PO_4 leaching issue for the contaminant tolerant FCs in harsh environments.

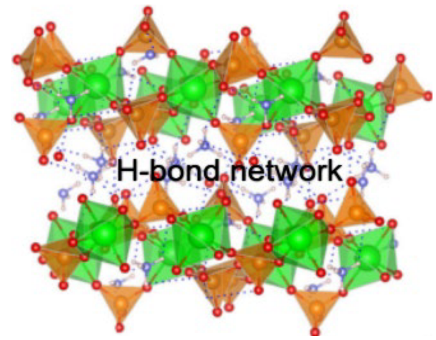


Figure 1. H-bond network in the layered structures of the inorganic proton conducting materials.

Currently, the proton conducting electrolyte powders (Figure 2) were obtained by a fluxing method. The production yield was improved from ~5% to ~50% by optimizing the conditions of synthesis, and material production is scaled up to 2 grams per batch. The electrolyte powder pellet (Figure 2B and 2C) shows a bulk proton conductivity of $\sim10^{-3}$ Scm^{-1} and a particles boundary conductivity of $\sim10^{-6}$-10^{-4} Scm^{-1} in the range of from room temperature to 150°C (Figure 3). The conductivity increases with the rise of temperature. The properties of the materials: thermal and chemical stability, composition and solubility, and the particles size impact on the proton conductivity were further analyzed and evaluated.

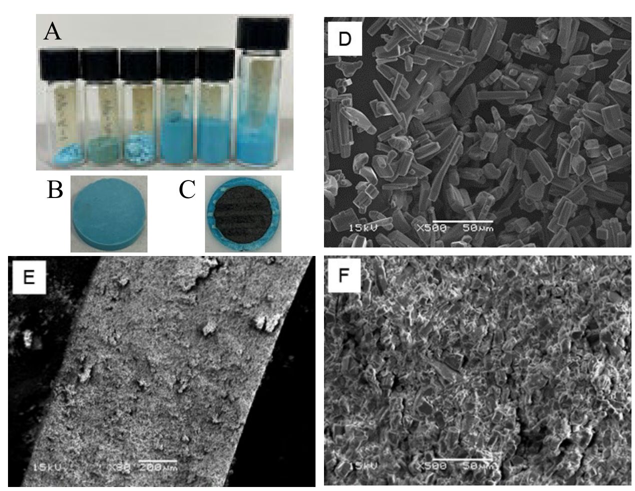


Figure 2. The pictures of the proton conductor powders (A) and the pellet (B, C). and the SEM images of the powders (D) and the cross-section of the pellet (E, F).

The material is insoluble in water, and thermal stable up to 300°C in inert or air environment, as well as electrochemically stable within the PEMFC cathode operating potential range but not below -0.1V or H_2/Pt environment. The proton conductivity in boundary/interface increases with the particle size decrease.

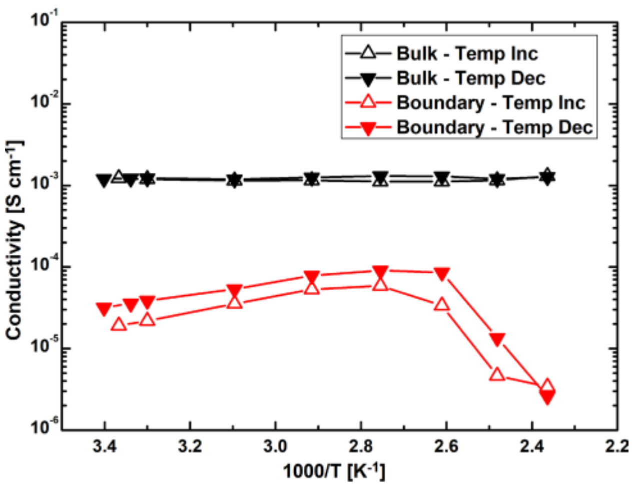


Figure 3. The bulk and boundary proton conductivity of the proton conducting particles at temperature 20-150°C.

Additionally, with collaboration of industrial and academic partners, a three-year $4M fuel cell project titled with "High Performing and Durable MEAs with Novel Electrode Structures and Hydrocarbon Proton Exchange Membranes" was awarded by U.S. DOE-EERE.

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

Funding Source: Office of Naval Research

Contact: Yunfeng Zhai, yunfeng@hawaii.edu

Last Updated: November 2024

E6: Advanced Characterization of PEMFC with Open Flow Field Architecture

OBJECTIVE AND SIGNIFICANCE: Proton exchange membrane fuel cells (PEMFCs) are energy conversion devices that offer high power densities at low operating temperatures making PEMFCs the most promising technology for many applications, such as automobiles, back-up power generating units, and portable devices. Commercial PEMFC systems utilize open flow field (OFF) architectures ensuring high power generation and excellent performance at high currents.

The project objective is to conduct a detailed evaluation of PEMFCs employing OFF design using advanced approaches like electrochemical impedance spectroscopy (EIS) and segmented cell system.

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

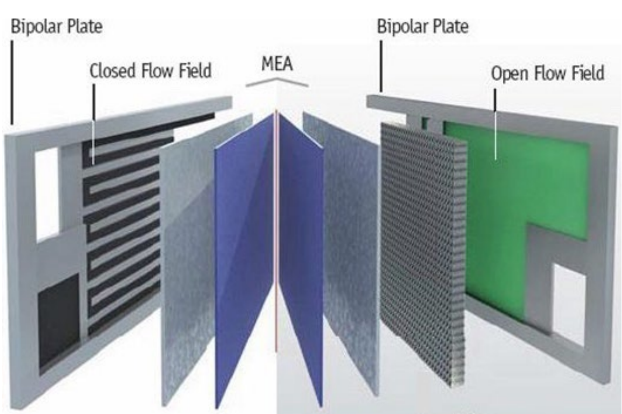


Figure 1. Schematic representation of fuel cell with open flow field.

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

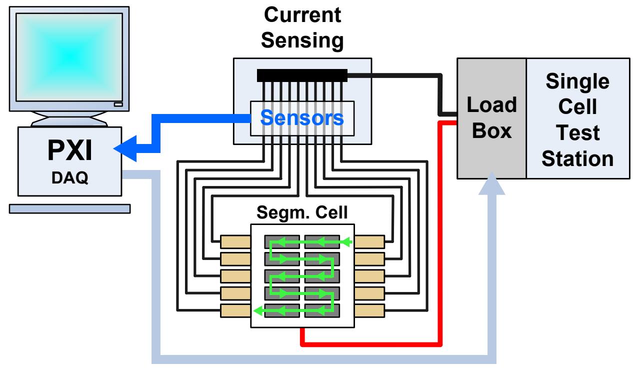


Figure 2. Schematic of segmented cell system.

PROJECT STATUS/RESULTS: During this project, feasibility of incorporation of the OFF to HNEI's segmented cell hardware was successfully demonstrated. Figure 3 on the following page shows polarization curves and high-frequency resistance (HFR) data recorded for L-C and OFF architectures and for selected locations of the MEA: Segment 1 (inlet), Segments 4 and 7 (middle), Segment 10 (outlet), and for the total cell.

Application of OFF led to higher performance of the MEA and provided uniform performance compared to L-C flow field design. At the same time, HFR values for both architectures were found to be very low and close (~30-50 mOhm cm^2). In addition, OFF ensured better heat transfer and heat dissipation, which is important for operation at high current.

An increase in performance for the OFF was attributed to minimal mass transport losses, highlighting the excellent gas transport and water management capabilities of Nuvera's flow field architecture.

Mass transport resistances (RMT) were determined for the OFF cell at different humidity levels (100/100, 100/50 and 50/50% RH) using distribution of limiting current approach developed at HNEI [1]. Results indicated that the mass transport resistance in gas phase ($R_{m, N2}$) and through the ionomer ($R_{film, CL}$) were lower compared to the L-C architecture contributing to the OFF cell's superior performance under high power-generating conditions (Table 1).

Table 1. Mass transport resistances determined for the OFF and L-C sample at different humidification, T=80°C.

Sample	RH [%]	$R_{film,CL}$ [s m^{-1}]	$R_{m,N2}$ @150kPa [s m^{-1}]
OFF	100/100	19.19	25.64
	100/50	37.65	30.97
	50/50	42.88	28.96
L-C [2]	50/50	46.12	93.35

Future work will include publication of the obtained results.

REFERENCES:

[1] T. V. Reshetenko, J. St-Pierre, J. Electrochem. Soc. 161 (2014) F1089.

[2] T. Reshetenko, O. Polevaya, Electrochim. Acta 387 (2021) 138529.

Funding Source: Nuvera Fuel Cells

Contact: Tatyana Reshetenko, tatyanar@hawaii.edu

Last Updated: November 2024

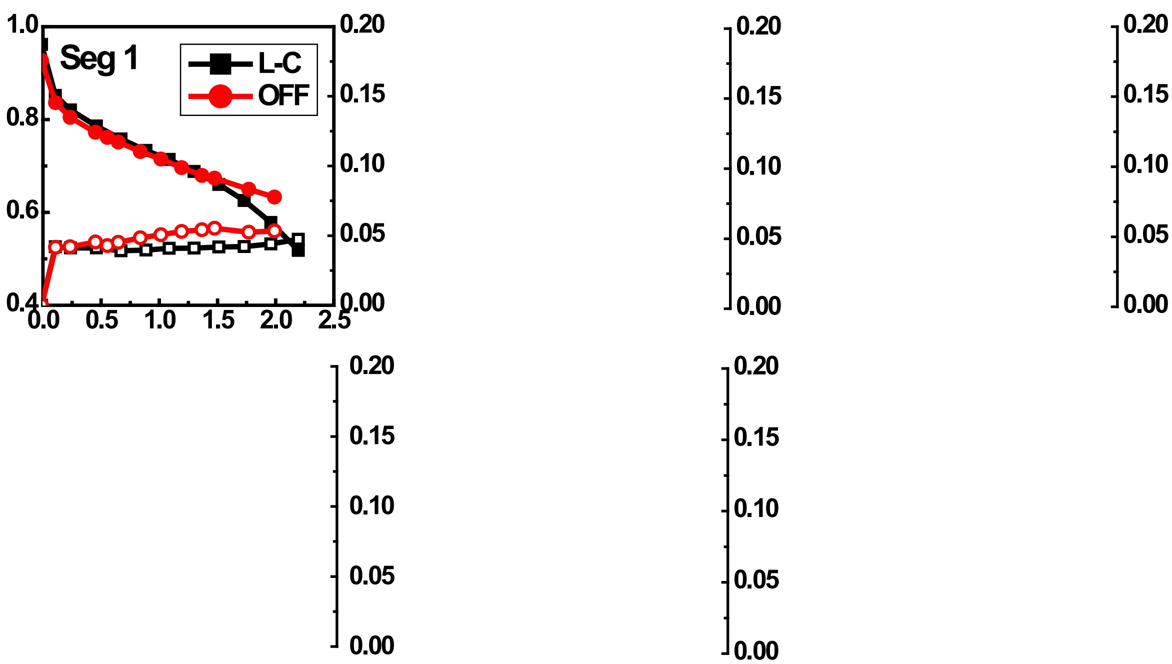


Figure 3. Local and total IV curves and HFR data for L-C and OFF flow field architectures. Operating conditions for An/Ca: H_2/air, 2/2 stoi, 100/50% RH, 150 kPa, 80°C.

E7: Proton Exchange Membrane Fuel Cell Producing Hydrogen Peroxide

OBJECTIVE AND SIGNIFICANCE: Hydrogen peroxide is widely useful to many industries, as well as the military, as an environmentally friendly disinfectant and liquid oxidant for air-independent fuel cell applications. The main method for hydrogen peroxide production today, an anthraquinone-oxidation process, is energy-intensive, expensive, produces waste that negatively impacts the environment, and is not easily scalable, leading to the transport of dilute solutions at high cost to minimize safety concerns.

The objective of this project is to modify a proton exchange membrane fuel cell (PEMFC) to allow electrochemical synthesis of hydrogen peroxide. The process also produces energy, eliminates waste by producing aqueous solutions of varied hydrogen peroxide concentrations, and is scalable to address the specific needs of these various industries and communities.

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

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

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

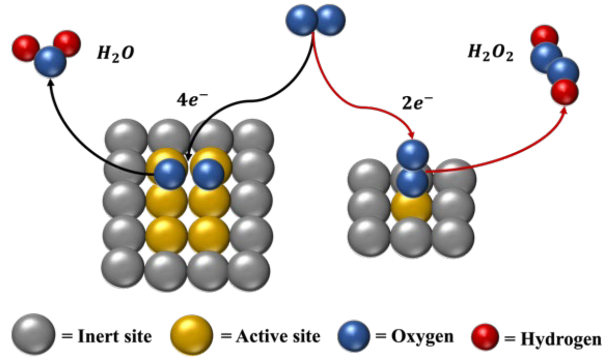


Figure 1. $2e^-$ and $4e^-$ pathways for the ORR.

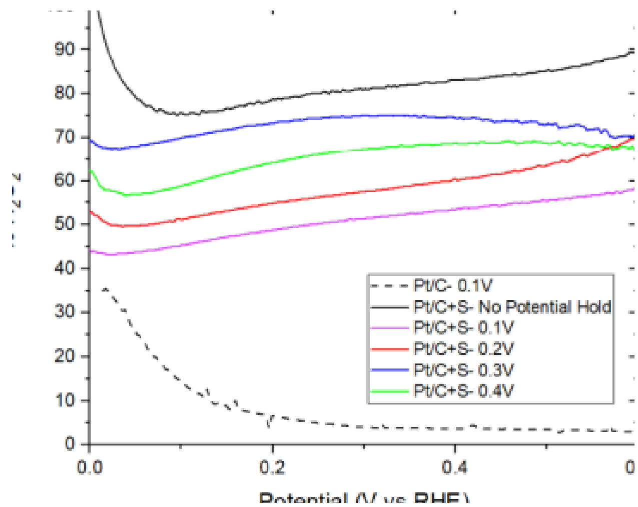


Figure 2. Hydrogen peroxide production vs potential for various deposition voltages in ex-situ test cell.

PROJECT STATUS/RESULTS: To date, HNEI has demonstrated viability of approach in ex-situ test cell producing > 50% yields of hydrogen peroxide. We also initiated test plans for in-situ experiments using 50 cm^2 single cells to determine optimal materials, system configuration, and process for producing and extracting hydrogen peroxide with a fuel cell.

This work resulted in an MS thesis titled "***Proton Exchange Membrane Fuel Cell Modification for Catalytic Cogeneration of Hydrogen Peroxide and Electricity***".

Funding Source: Office of Naval Research

Contact: Edward Bruffey, ebruffey@hawaii.edu

Last Updated: November 2024

Hawai‘i Natural Energy Institute Research Highlights

Appendix E: Electrochemical Power Systems

E8: Path Dependence of Battery Degradation

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

<u>Background</u>: Electrification of transportation and grid-storage are crucial to combat climate change. Understanding and mitigating battery degradation is key to improving durability of electric transportation and the reliability of power grids. Complexity stems from the fact that battery degradation is path dependent. This implies that usage affects not only the degradation pace, but also the type of degradation the batteries experience. Lithium-ion batteries are known to degrade slowly at first before a rapid acceleration of which starting time will depend on the mix of degradation mechanisms and thus on how the battery was used. To maximize the utility of large battery systems, it is essential to understand the impact of all the stress factors associated with an application and their combined effects.

<u>Project Status/Results</u>: Our study already showed that a simplistic approach to V2G, namely that an EV is discharged at constant power for 1 hour without consideration of battery degradation, is not economically viable because of the impact additional V2G cycling has on battery life. However, we showed that if the batteries are to be used for frequency regulation, there is a much lesser impact. We also showed that, with good battery prognostic models and further advances in understanding the causes, mechanisms, and impacts of battery degradation, a smart control algorithm could take all these aspects in consideration and make V2G and fast charging a reality. It must be noted that, because of path dependence, different usages might lead to different results and thus that our results should not yet be generalized on cells different than the one tested.

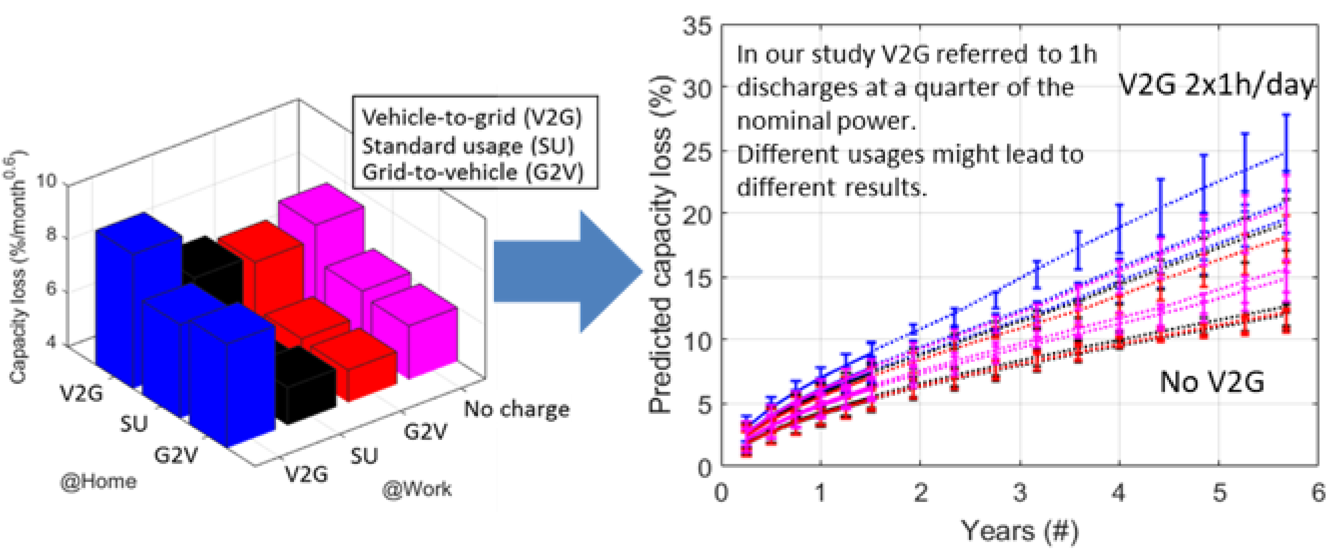
Current work with DSTG (Australia) involves an experimental campaign of more than 700 cells tested under a HNEI-defined design of experiments to predict the degradation of MW systems and maximize durability and reliability in the field. Collaborative work is also ongoing with Sandia National Laboratories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

Research conducted for this project is completed in the **PakaLi Battery Laboratory**. This project is ongoing and has led to 13 publications, which are listed on the following page.

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

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2024



ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

1. 2023, R. Wittman, et al., **Characterization of Cycle-Aged Commercial NMC and NCA Lithium-ion Cells: I. Temperature-Dependent Degradation**, Journal of The Electrochemical Society, Vol. 170, Issue 12, Paper 120538. (Open Access: **PDF**)
2. 2023, A. Gismero, et al., **The Influence of Testing Conditions on State of Health Estimations of Electric Vehicle Lithium-Ion Batteries Using an Incremental Capacity Analysis**, Batteries, Vol. 9, Issue 12, Paper 568. (Open Access: **PDF**)
3. 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**)
4. 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**)
5. 2020, M. Elliott, et al., **Degradation of electric vehicle lithium-ion batteries in electricity grid services**, Journal of Energy Storage, Vol. 32, Paper 101873.
6. 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**)
7. 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**)
8. 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**)
9. 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**)
10. 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.
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, 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.
13. 2016, D. Ansean, et al., **Fast charging technique for high power LiFePO4 batteries: a mechanistic analysis of aging**, Journal of Power Sources, Vol. 321, pp. 201-209.

PRESENTATIONS:

1. 2022, R. Wittman, et al., **Path Dependence of Li-Ion Battery Degradation During Cycling to 80% Capacity**, Presented at the Material Research Society Spring Meeting, May 8-13.
2. 2021, R. Wittman, et al., **Characterizing Materials and Electrochemical Changes in a Range of 18650 Li-Ion Cells Cycled to 80% Initial Capacity**, Presented at the 239th ECS Meeting, Chicago, IL, May 30-June 3.
3. 2019, M. Dubarry, et al., **Synthetic vs. Real Driving Cycles: A Comparison of EV Battery Degradation**, Presented at the 236th ECS Meeting, Atlanta, Georgia, October 13-17.
4. 2019, G. Baure, et al., **A Diagnostic and Prognostic Study of the Impact of Electric Utility Grid Operations on EV Batteries**, Presented at the International Coalition for Energy Storage and Innovation Meeting, Waikoloa, Hawaiʻi, January 5-10.
5. 2017, A. Devie, et al., **Durability and Reliability of EV Batteries under Electric Utility Grid Operations**, Presented at the 232nd ECS Meeting, National Harbor, Maryland, October 1-5.

E9: Battery Intelligence: Diagnosis and Prognosis

OBJECTIVE AND SIGNIFICANCE: This project aims at the development of approaches, tools, and protocols to improve batteries diagnosis and prognosis via non-invasive in-operando techniques.

BACKGROUND: Battery diagnosis and prognosis is a difficult task. Lithium- and Sodium-ion batteries 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 multitude of sensors is precluded.

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

This assessment of state of the art led HNEI to define and develop a third industry-compatible intermediate route to reach an accurate diagnosis with cost-effective and non-destructive methods, using only sensors already available in battery packs while requiring limiting computing power. HNEI developed a mechanistic modeling framework where a battery digital twin is built from individual electrode data and where the battery degradation is emulated by the scaling or the translation of one electrode versus the other. Using this framework, the voltage variations associated with the degradation mechanisms can be predicted.

Machine learning and artificial intelligence are also starting to play a crucial role in diagnosing and prognosing batteries. However, their accuracy is limited by the little to no training data available to validate algorithms. To solve this issue, HNEI applied the mechanistic modeling approach to develop the first synthetic training datasets. Recent work highlighted the possible opportunistic diagnosis of battery usage for photovoltaic-connected batteries using models trained and validated on synthetic datasets.

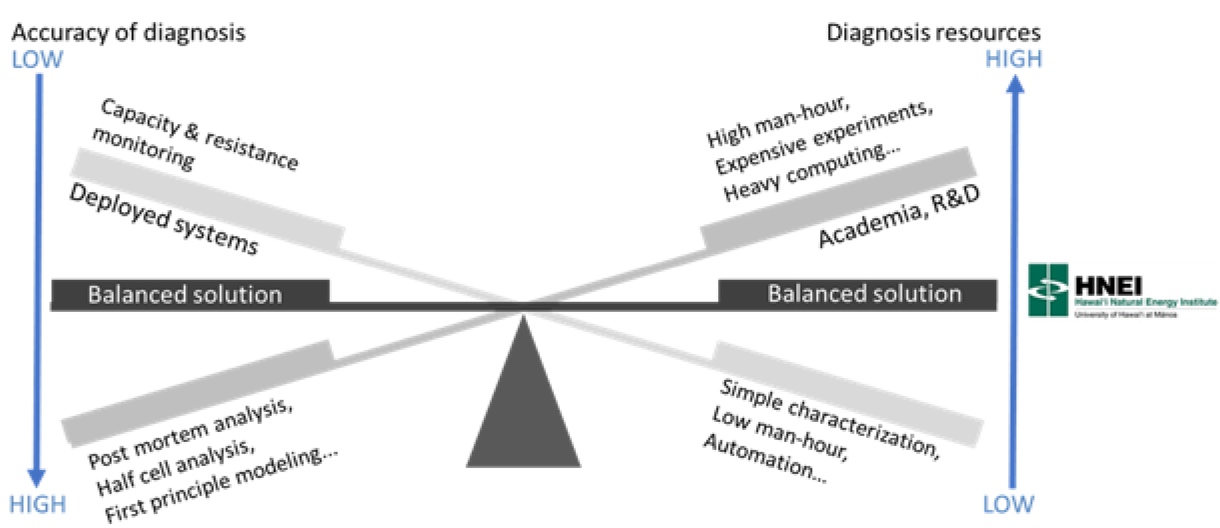
Research conducted for this project is completed in the **PakaLi Battery Laboratory**.

PROJECT STATUS/RESULTS: This project is currently ongoing with three industrial collaborations on different aspects of the problem including blends, silicon content, relaxation, and metal plating. A full suite of software and models were developed. The main model has been licensed by more than 135 organizations worldwide. This work has also led to 51 publications, many of which are linked on the following pages, and one patent.

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

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2024



ADDITIONAL PROJECT RELATED LINKS

PAPERS AND PROCEEDINGS:

Battery Testing

1. 2024, M. Dubarry, et al., **Communication—Forecast of the Impact of Degradation Modes on a Commercial Hard Carbon/$Na_3V_2(PO_4)_2F_3$-based Na-ion Battery**, Journal of the Electrochemical Society, Vol. 171, Issue 8, Paper 080541. (Open Access: **PDF**)
2. 2024, A. Fernando, et al., **Voltage relaxation characterization methods in lithium-ion batteries**, Measurement: Energy, Vol. 3, Paper 100013. (Open Access: **PDF**)
3. 2024, A. Fernando, M. Kuipers, G. Angenendt, K-P. Kairies, M. Dubarry, **Benchmark dataset for the study of the relaxation of commercial NMC-811 and LFP cells**, Cell Reports Physical Science, Vol. 5, Issue 1, Paper 101754. (Open Access: **PDF**)
4. 2022, M. Dubarry, et al., **Best practices for incremental capacity analysis**, Frontiers in Energy Research, 10:1023555. (Open Access: **PDF**)
5. 2022, L. Ward, et al., **Principles of the Battery Data Genome**, Joule, Vol. 6, Issue 10, pp. 2253-2271. (Open Access: **PDF**)
6. 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**)
7. 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**)
8. 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**)
9. 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.
10. 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.
11. 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**)
12. 2019, A. Barai, et al., **A comparison of methodologies for the non-invasive characterisation of commercial Li-ion cells**, Progress in Energy and Combust. Sci., Vol. 72, pp. 1-32. (Open Access: **PDF**)
13. 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.
14. 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**)
15. 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**)
16. 2017, D. Anseán, 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.
17. 2016, D. Anseán, 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. 2024, M. Dubarry, et al., **Investigation of the impact of different electrode inhomogeneities on the voltage response of Li-ion batteries**, Cell Reports Physical Science, Vol. 5, Paper 102138. (Open Access: **PDF**)
2. 2024, D. Beck, et al., **Electrode Blending Simulations Using the Mechanistic Degradation Modes Modeling Approach**, Batteries, Vol. 10, Issue 5, Paper 159. (Open Access: **PDF**)

3. 2024, N. Costa, et al., **ICFormer: A Deep Learning model for informed lithium-ion battery diagnosis and early knee detection**, Journal of Power Sources, Vol. 592, Paper 233910. (Open Access: **PDF**)
4. 2023, M. Dubarry, et al., **Data-Driven Diagnosis of PV-Connected Batteries: Analysis of Two Years of Observed Irradiance**, Batteries, Vol. 9, Issue 8, Paper 395. (Open Access: **PDF**)
5. 2023, M. Dubarry, et al., **Accurate LLI and LAM_{PE} Estimation Using the Mechanistic Modeling Approach with Layered Oxides**, Journal of The Electrochemical Society, Vol. 170, Paper 070503. (Open Access: **PDF**)
6. 2023, M. Dubarry, D. Howey, B. Wu, **Enabling battery digital twins at the industrial scale**, Joule, Vol. 7, Issue 6, pp. 1134-1144. (Open Access: **PDF**)
7. 2023, M. Dubarry, N. Costa, D. Matthews, **Data-driven direct diagnosis of Li-ion batteries connected to photovoltaics**, Nature Communications, Vol. 14, Paper 3138. (Open Access: **PDF**)
8. 2022, M. Dubarry, et al., **Perspective on Mechanistic Modeling of Li-Ion Batteries**, Accounts of Material Research, Vol. 3, Issue 8, pp. 843-853.
9. 2019, S. Schindler, et al., **Kinetics accommodation in Li-ion mechanistic modeling**, Journal of Power Sources, Vol. 440, Paper 227117.
10. 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**)
11. 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**)
12. 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.
13. 2016, M. Dubarry, et al., **Cell-balancing currents in parallel strings of a battery system**, Journal of Power Sources, Vol. 321, pp. 36-46.
14. 2016, M. Berecibar, et al., **Degradation Mechanism Detection for NMC Batteries based on Incremental Capacity Curves**, World EV Journal, Vol. 8, Issue 2, pp. 350-361. (Open Access: **PDF**)
15. 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.

PRESENTATIONS:

5. 2023, M. Dubarry, et al., **Effect of Temperature on Lithium-Ion Battery Voltage Response and How to Model It in the Mechanistic Modeling Approach**, Presented at the 244th Electrochemical Society Meeting, Goteborg, Sweden, October 8-12.
6. 2023, M. Dubarry, et al., **Big data for the diagnosis and prognosis of deployed energy storage systems**, Presented at the Energy Storage Systems Safety & Reliability Forum, Santa Fe, NM, June 6-8.
7. 2023, A. Fernando, et al., **A Study of the Relaxation Patterns of Commercial Cells**, Poster presented at the International Battery Association Conference, Austin, TX, March 5-10.
8. 2022, M. Dubarry, **Big Data in Diagnostics Data-Driven Direct Diagnosis of PV Connected Batteries**, Presented at the Advanced Automotive Battery Conference, San Diego, California, December 7-9.
9. 2022, M. Dubarry, et al., **Mechanistic Li-Ion Battery Modeling, What's Next?**, Presented at the 242th ECS Meeting, Atlanta, GA, October 9-13.
10. 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.
11. 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.
12. 2021, M. Dubarry, et al., **A New Insight into Blended Electrodes**, Presented at the 240th ECS Meeting, Orlando, Florida, October 10-14.
13. 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.

E10: Battery Electrode Optimization

Objective and Significance: This project aims at the optimization of battery electrodes to improve performance by understanding local degradation mechanisms and by tuning the electrode architecture.

Background: Advanced energy conversion devices typically rely on composites electrodes made of several materials interacting with one another. Understanding their individual and combined impact on degradation is essential in the pursuit of the best possible performance and safety. In this project, we use our expertise in Li-ion battery diagnosis as well as designs of experiments (DoE) to optimize formulations and to investigate the importance of process parameters while minimizing resources.

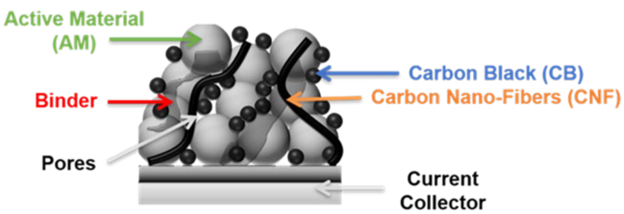


Figure 1. Schematic of the typical electrode architecture for intercalation-based batteries.

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

Project Status/Results: In this project, the DoE approach was applied to two types of electrodes: high power electrodes for lithium batteries (ONR funded, in collaboration with the University of Montreal) and sodium intercalation electrodes to investigate the feasibility of desalination batteries (DOI then ONR funded, in collaboration with Trevi Systems). In addition, recent work focused on battery cooling and the development of a thermal dummy cell that thermally behaves like a battery without the risks associated with it. Taking a segmented approach will allow to account for the impact of thermal gradients, a major issue impacting cell durability and safety.

A high-power battery system was optimized in collaboration with the University of Montreal. This work has led to two publications. Current work on the desalination batteries showcased that Prussian blue analogues can intercalate and release sodium ions in real sea water more than 15,000 times with improved performance compared to traditional materials (CDI).

Finally, a first prototype of the segmented thermal dummy cell demonstrated the potential of the approach for the safe development of new innovative cooling solutions.

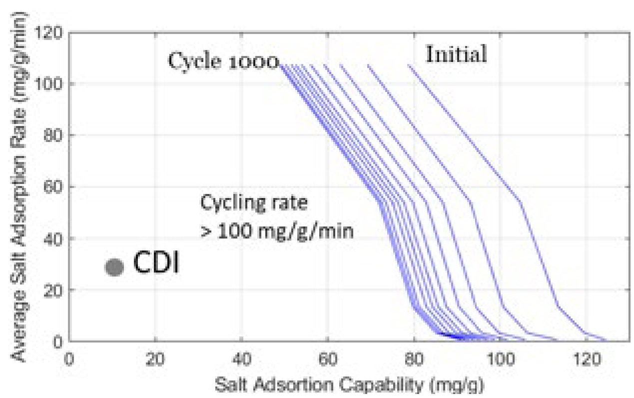


Figure 2. Performance characteristics of novel intercalation materials for desalination batteries.

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

Research conducted for this project is completed in the [PakaLi Battery Laboratory](). This program has led to three publications and several presentations, which are listed on the following page.

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

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

Contact: Matthieu Dubarry, matthieu@hawaii.edu

Last Updated: November 2024

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

F1: Printable Photovoltaics

OBJECTIVE AND SIGNIFICANCE: The objective of this project is to develop high-throughput ink-based fabrication techniques for lightweight 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 on rooftops and centralized production plants, are easily recognizable by their architecture, with interconnected wafer-like solar cells laminated under a flat sheet of glass. Although well-suited for stationary electrical production, the mechanical rigidity and weight of silicon PV modules become a burden for mobile applications, where portability is more critical than performance. To this end, R&D efforts have focused on methods to integrate ultra-light and flexible thin film solar materials onto lightweight/flexible substrates, including plastics (polyamides) and fabrics. Such devices can generate enough electricity to power small electronic devices for both civilian and military applications such as phones, electronic tablets, and sensors.

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

The research is currently focused on a multi-compound alloy ($CuInSe_2$, CISe) − a material which meets the mechanical and weight requirements for lightweight, 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.

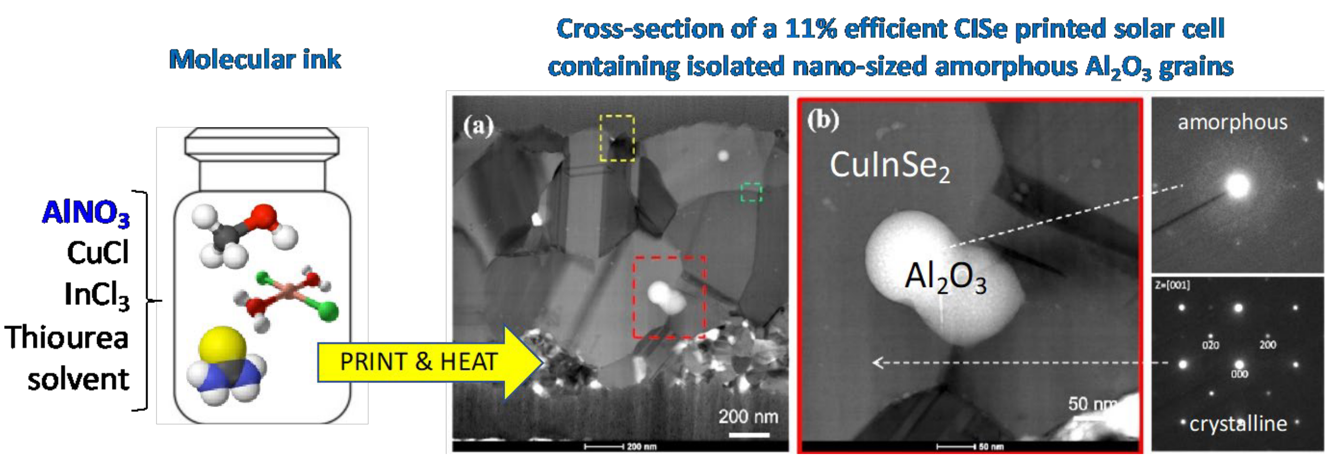
To date, this research has produced the following publication:

- 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

Contact: Nicolas Gaillard, ngaillar@hawaii.edu

Last Updated: November 2024



F2: Two-Dimensional Materials for Thin Film Manipulation

OBJECTIVE AND SIGNIFICANCE: Through this project, our objective is to develop methodologies to facilitate the manipulation of thin films utilizing two-dimensional (2D) interfacial layers. This approach has the potential to facilitate the physical transfer of high-efficiency devices, such as photovoltaics, from their original substrates to novel platforms, including clothing, vehicles, and buildings.

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

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

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

Current efforts are focused on: 1) the exfoliation of commercially available 2D materials; 2) the characterization of their chemical properties using advanced spectroscopic techniques; and 3) the theoretical modeling of their energetics when interfaces with CIGSe.

Graphene and $MoSe_2$ 2D layers were isolated through the mechanical exfoliation method. Flakes of both materials were delaminated from bulk seed crystals by pressing a transfer strip onto them. The process involved folding the tape on itself a predetermined number of times to further separate the remaining crystals. Subsequently, these separated layers were transferred onto silicon wafers. X-ray photoelectron spectroscopy and Raman spectroscopy carried out at UNLV and HNEI, respectively, evidenced the 2D nature of the layers isolated with HNEI's method.

Lastly, theoretical modeling efforts conducted at both UH and LLNL focused on understanding the impact of mechanical strain on the energetic properties of 2D materials. This crucial information will be instrumental in analyzing how mechanical deformation, such as stretching or bending, affects the performance of flexible PV devices.

To date, this research has produced the following work:

- 2024, M. McLean, A.T. Nguyen, W. Lee, and N. Gaillard, **Periodically Strained 2D Materials for Tunable Optoelectronic Applications**, Presented at the Electrochemical Society PRiME Meeting, October 6-11, Symposium H03, Abstract 2468.

Funding Source: U. S. Department of Energy

Contact: Nicolas Gaillard, ngaillar@hawaii.edu

Last Updated: November 2024

F3: Encapsulation of Perovskite Solar Cells for Long Term Operations

OBJECTIVE AND SIGNIFICANCE: The primary objective of this program is to invent innovative encapsulation techniques that can enhance the operational lifespan of emerging low-cost, high-efficiency perovskite solar cells (PSCs). These advancements have the potential to help the U.S. Department of Energy (DOE) meet its commitment to reducing the cost of photovoltaics to $0.02/kWh, making solar energy more accessible and affordable.

BACKGROUND: Since the first report of PSCs in 2009, tremendous research efforts on absorber chemistry have boosted the power conversion efficiency of this material class from 3.9% to 25.7%. Although impressive, this attribute alone cannot guarantee the commercial success of PSCs, as any emerging technology must also meet the 20-25 year stability already achieved by other mature photovoltaic (PV) classes. To date, the durability of best performing PSCs is limited to a few months at best, constituting an important roadblock in their deployment.

PROJECT STATUS/RESULTS: In this project, HNEI partners with the National Renewable Energy Laboratory (NREL) to accelerate the development of unique protection schemes to enhance PSCs lifetime. Specifically, our team aims at eliminating two stress factors responsible for PSC degradation: high temperatures during processing (technical barrier #1) and atmospheric effects during PV operations (technical barrier #2).

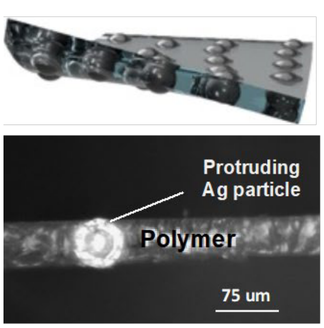
HNEI has developed a new composite integrating multi-functionalities, such as *corrosion resistance*, *lightweight* and *flexibility*, as well as *tunable optoelectronics*. Unlike most conductive flexible polymers, where media are coated on top providing only *in-plane* conductivity, HNEI's transparent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

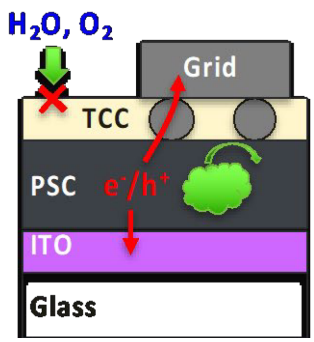
In this project, TCCs serve as gas-barrier located between the PSC and metal top contacts, providing a conformal hermetic seal repelling moisture and oxygen while preventing out-diffusion of volatile species. TCCs offer at least three main advantages over traditional "glass-glass" encapsulation.

First, our composite fully cures at room temperature (addressing barrier #1) – eliminating all adverse thermal effects encountered in conventional sealant/adhesive technologies, which require curing above 100°C. Also, the protruding particles in TCC act as direct electrical access points to the underlaying structure. Therefore, the coating is not spatially restricted and can be applied directly on top of the PSC and can extend to the device edges, sealing directly the top and sides of the PV stack to the operating environment (addressing barrier #2) with no risk of lateral electrical shorting. Finally, there is no need for an extra encapsulating glass cover with TCCs, reducing module weight and cost.

Our team has demonstrated that TCCs can maintain virtually 100% of their optical and electrical properties for over 1,000 hours of outdoor exposure under Hawaiʻi's tropical semi-arid climate, while TCC-coated PSCs preserve over 90% of their initial efficiency after 1,300 hours of accelerated testing under 45% relative humidity at 50°C.

Current efforts are focused on reducing TCC's water vapor and oxygen transmission rates to meet packaging standards.





To date, this research has produced the following works:

- 2024, K. Outlaw-Spruell, J. Xu, Q. Jiang, K. Zhu, and N. Gaillard, **Transparent Conductive Composites – Novel Encapsulation Scheme for organic photovoltaics show potential as a dual functioning transparent electrode and barrier system**, Poster presented at the U.S. DOE Solar Energy Technology Office Peer Review, March 26-27, Washington, DC Photovoltaics Research Track.
- 2023, K. Outlaw-Spruell, J. Xu, Q. Jiang, K. Zhu, and N. Gaillard, **Transparent Conductive Composites—A New Class of Encapsulants for Durable Perovskite Photovoltaics**, Presented at the Materials Research Society Spring Meeting, April 10-14, San Francisco, California, Symposium EL02.17.04.

Funding Source: U. S. Department of Energy

Contact: Nicolas Gaillard, ngaillar@hawaii.edu

Last Updated: November 2024

F4: Development of Novel Air Filtration Materials

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

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

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

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

We finalized the SO_2 sorption performance testing of the synthesized and characterized novel metallo-ionic liquids (MIL): $Zn_3[OAc]_8[C_2mim]_2$, $Mg_4[OAc]_{10}[C_2mim]_2$, and $Fe_4[OAc]_{10}[C_2mim]_2$ supported on nanoporous activated carbon (AC). The Mg-based MIL-AC sorbents had the highest SO_2 breakthrough time and capacity followed by Zn-based sorbent (Figure 1). The sulfur dioxide tests were performed at 10 ppm in simulated air, using a custom-designed and fabricated filtration materials test stand, at 1.5 LPM and relative humidity of 40-50%.

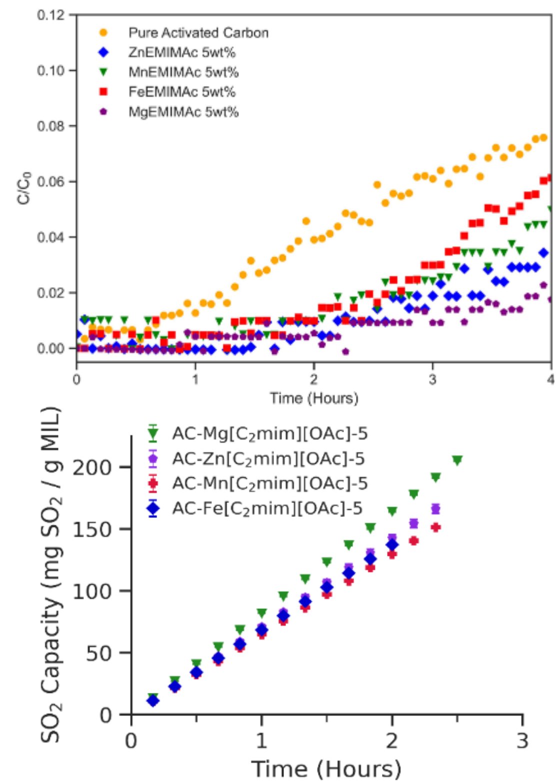


Figure 1. Comparative studies of SO_2 absorption for 5 wt% MIL-AC under a challenge gas of 10 ppm SO_2.

Further work involves integration of the $Zn_3[OAc]_8[C_2mim]_2$ and $Mg_4[OAc]_{10}[C_2mim]_2$ with commercial filter media to form improved hybrid filters for multiple gas contaminant removal and investigating capability of the metallo ionic liquids for H_2S removal.

Funding Source: Office of Naval Research

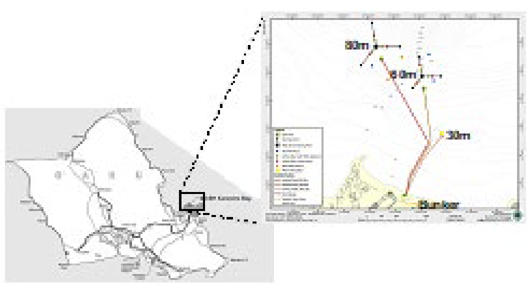
Contact: Godwin Severa, severa@hawaii.edu

Last Updated: November 2024

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

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

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



<u>BACKGROUND</u>: Wave energy also has enormous potential to supply persistent power to small-scale or non-grid-connected applications, including ocean observation, charging of autonomous vehicles, aquaculture, at-sea mineral scavenging, and providing renewable power to remote or island communities. Through a cooperative effort between the Navy and the U.S. Department of Energy (DOE), WETS hosts companies seeking to test their pre-commercial WEC devices in an operational setting. HNEI works with the Navy and DOE to directly support WEC testing at WETS in three key ways: 1) *environmental impact monitoring* – acoustic signature measurement and protected species monitoring; 2) independent *WEC device performance analysis*, including wave forecasting and monitoring, power matrix development (power output versus wave height and period), numerical hydrodynamic modeling, and a regimen of regular WEC and mooring inspections; and 3) *logistics support*, in the form of past funding to modify a site-dedicated support vessel for use at WETS, through local partner Sea Engineering, Inc., assisting WEC developers with deployment planning and through funding to developers for maintenance actions during their WEC deployments at the site.

In Summer 2022, NAVFAC granted HNEI an additional $3.7M 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. Research continues in three primary areas: 1) 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; 2) advancement of a novel breakwater system with integrated OWC power generation; and 3) concept development and testing of a floating flap-type WEC.

Funding to support this research, as well as funds for all WETS support functions (including several major site infrastructure repairs and enhancements), has now totaled over $34M.

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

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

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

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

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

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

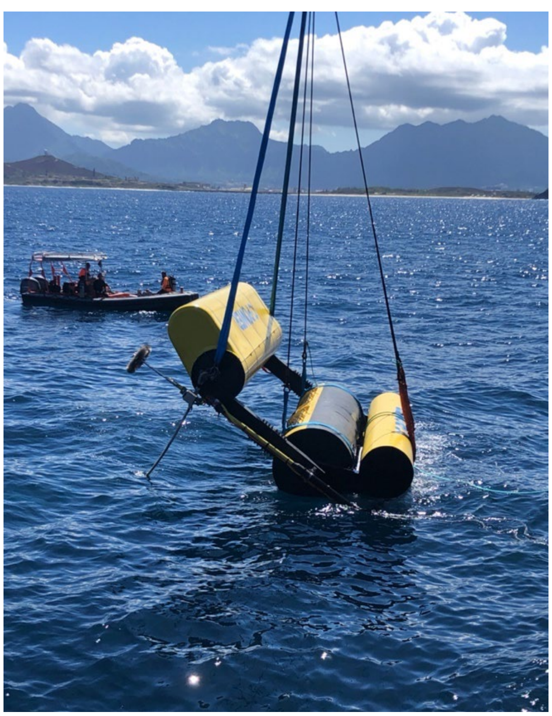
- November 2019: Completion of site-dedicated support vessel Kupa‘a by research partner Sea Engineering, Inc. This vessel adds significantly to our ability to perform various functions at WETS.

Issues stemming from COVID, funding, and technical challenges have substantially delayed planned WEC deployments over the past few years, but three deployments are currently happening, or are planned in the coming year:

1. Deployment of the Oscilla Power (Seattle) Triton-C community-scale WEC at the 30m berth. This device arrived in Hawai‘i in October 2021. New anchors were deployed at the WETS 30m berth in support of this project, with work complete in August 2022, and a new electrical/data junction box was installed in

September 2023. The device is currently ready for deployment, pre-staged at Marine Corps Base Hawaiʻi, and will deploy during the next weather window of less than 3-foot seas for 3 days, which is not a common occurrence.

2. Deployment of the C-Power SeaRay WEC. This is a stand-alone (not grid-connected) deployment of a small, 1 kW device designed to feed power to a subsea battery system that in turn provides power to an acoustic sensing system from Biosonics, as well a seafloor AUV docking station from Hibbard Inshore. The device was deployed at WETS in early October 2023 but suffered some early damage. It was redesigned and redeployed in June/July 2024, and successfully demonstrated wave power extraction and battery charging.



3. Deployment of the Ocean Energy (Ireland) OE35 WEC at the 60m berth. This device has been in Hawaiʻi since December 2019, and underwent drydock repairs in August/September 2022, after extensive delays. A new generator was installed in April/May 2024, and it was deployed to WETS in July. However, it is not yet operational, as weather and logistics have not yet supported the operation to connect its umbilical cable to the WETS shore cable. It is hoped this will be achieved soon.

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

Contact: Patrick Cross, pscross@hawaii.edu

Last Updated: November 2024

G2: The Hawaiʻi Wave Surge Energy Converter (HAWSEC)

<u>Objective and Significance</u>: The objective of the Hawaiʻi Wave Surge Energy Converter (HAWSEC) project, funded primarily by the U.S. Department of Energy (DOE), is to mature a wave energy converter (WEC) concept developed by the HNEI-led team, that could ultimately produce cost-effective renewably generated electricity for coastal communities. The project is expected to make important advances in the emerging wave energy field and has the potential to mature a technology with realizable commercial potential in the future for Hawaiʻi, the U.S., and beyond.

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

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

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

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

<u>Project Status/Results</u>: This project was initated in August 2020. HAWSEC development is proceeding along the following broad set of tasks:

1. Numerical modeling of small-scale version, nominally a 1m x 1m flap, to optimize design;
2. Fabrication and local testing of the small-scale system, both the hydraulic system and the flap itself, in nearshore waters on Oʻahu;
3. Controlled tank testing of the small-scale system at Oregon State University's (OSU) Hinsdale wave basin;
4. Validation of numerical modeling with test results from OSU;
5. Numerically scaling up to medium scale, nominally a 3m x 3m flap, and completing a buildable design of the HAWSEC at this scale;
6. Undergoing a Go/No-Go decision with DOE;
7. Fabrication of the power takeoff (PTO) for a medium scale system;
8. Laboratory testing of the medium-scale PTO; and
9. Validation of medium-scale numerical models with test data, and modeling and performance prediction for a full-scale version of HAWSEC.

A hydraulic bench test setup was completed in our lab on the UH campus in early 2022, including a linear actuation system that is capable of simulating realistic wave forcing. Lab testing was carried out between January and May 2022, resulting in readiness to ship the full system to Oregon for wave basin testing at OSU.

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

Figure 2. Flap testing at the Makai Research Pier.

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

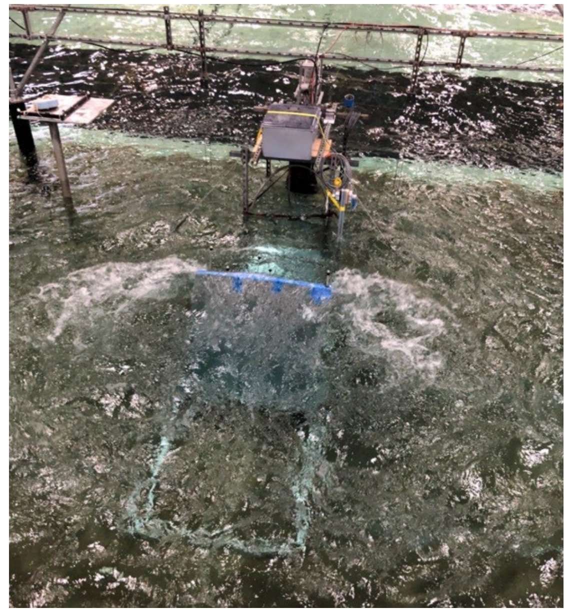


Figure 3. Controlled wave basin testing at OSU.

In February 2024, we successfully got through the Go/No-go decision from DOE. While there have been some administrative and process delays, the work under the second budget period has begun, with the project expect to wrap up in early 2026.

This extended timeline stems from substantial procurement challenges in Budget Period 1 and a shipping-related setback, which cost the project several months. Despite these delays, the project is meeting its technical objectives and has resulted in a WEC concept that is of high interest to DOE and to our partners at the National Renewable Energy Lab, who are now working with us on a new project that is utilizing our small-scale flap for a PTO development of their own and subsequent deployment at Makai Pier, which is expected to begin in summer 2025.

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

Contact: Patrick Cross, pscross@hawaii.edu

Last Updated: November 2024

H1: Asia Pacific Regional Energy System Assessment (APRESA)

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

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

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

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

USAID partner country governments need high-quality technical expertise to guide their decision-making and can learn from the experience of more developed countries using their best practices and case studies. With significant experience providing technical expertise in the renewable energy space, HNEI is uniquely positioned to partner with USAID and provide energy intelligence in identifying tailored solutions for jurisdictions in need. This collaborative approach, leveraging the capabilities, resources, and know-how of HNEI and USAID implementing contractors in the Asia-Pacific region is consistent with the U.S.' whole-of-government strategy to grow sustainable and secure energy markets across the region. Achieving self-reliance enables emerging economies to rely less on external aid in times of crisis, promotes more transparent markets that incentivize private investment, and redirects resources from inefficient energy subsidies toward more productive utilization. Low-cost renewable energy has the potential to improve the financial viability of energy sectors, reduce vulnerabilities to malign and climate change influences, and improve a country's overall ability to finance its self-reliance. HNEI's collaborations and interventions under this grant help deliver technical expertise to policymakers in emerging economies that can aid in achieving lower-cost, cleaner energy solutions that catalyze competitive markets and reduce carbon emissions – ultimately enabling their populations to enjoy universal, reliable, and cleaner electricity services.

HNEI is using the remaining APRESA funding to complete the efforts in the current countries and to expand this work to select other locations with particular focus on Pacific Island countries (PICs). These efforts are supported by several HNEI faculty and staff, including those of the HNEI's Grid System Technologies Advanced Research Team (Grid*START*). Relative to its recent engagements in PICs, HNEI Grid*START* has launched a new partnering arrangement with the Japan International Cooperation Agency (JICA) and its prime contractor, Okinawa Enetech, in joint Pacific region energy transition technical support to PICs. In 2024, HNEI is jointly delivering with Enetech technical support to

Palau on a range of issues. Discussions are underway with JICA and Enetech to expand on the collaborative successes in Palau and jointly deliver further support to other PICs in 2025.

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

Vietnam

Innovation System Mapping Project in the Renewable Energy Sector

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

In April 2023, NISTPASS held a workshop with various Vietnamese groups titled "Mapping Sector Innovation System of Renewable Energy in Vietnam," which was attended by HNEI and ONR personnel. Incorporating inputs from this workshop, NISTPASS produced a final deliverable book titled "Sectoral Innovation System in Renewable Energy: Case of Solar and Wind in Vietnam," along with a SIS stakeholders' analysis report. This project was largely completed at the end of 2023. Final reporting and payments are being completed.

Saigon Energy Hub (SEHub) Support

HNEI is collaborating with Ho Chi Minh City's Institute for Regional and Urban Studies (IRUS) to develop a public renewable demonstration and technology center to raise the community awareness of the needs, the feasibility, and the benefits of energy efficiency and renewable energy. Originally planned for an outdoor public park venue, the project now consists of a number of energy efficiency and renewable energy themed workshops being conducted at new facilities located at Ho Chi Minh City Union of Science and Technology Association's Headquarters.

To date, six workshops covering carbon credits, offshore wind power, legal framework regarding energy savings, energy management, integrated infrastructure and transit-oriented development, and GIS as an effective urban management tool have been conducted. Eleven speakers have contributed, and 260 stakeholders (online and in-person) have participated. Participation has ranged from researchers, technology associations, and business owners to policy makers. The last two workshops are planned for early 2025. This work is described in more detail in Appendix H2.

Institute of Energy (IoE) and HNEI MOU

Collaborations originally planned under an existing HNEI and EREA (Electricity and Renewable Energy Agency) MOU continue, but via collaboration with a different group within the Ministry of Industry and Trade – the Institute of Energy (IoE). HNEI met with IoE in April 2023 and again in September 2024 to finalize discussions of an MOU and to define the near-term scope of the research collaboration. Consistent with previous discussions, it was also agreed that HNEI would support training of the IoE staff to facilitate development of a high-fidelity dispatch model of the Vietnamese grid system. A detailed scope of work and schedule has been agreed to with training to be initiated in December 2024.

Thailand

Provincial Electricity Authority of Thailand (PEA) Collaboration

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

Since Spring 2020, HNEI Grid*START* has delivered a training program for PEA select engineers. The program accommodates two classes of up to six engineering interns each year. The program lasts for twelve weeks and includes 40 hours of lectures and team-oriented deep immersion in custom "hands-on mini project" research, development, and test endeavors tailored to the learning needs of working utility engineers focused on energy distribution systems. While the program was paused due to Thailand's political climate following the 2023 elections, the program is poised to resume in February 2025 with HNEI welcoming a new group of engineering interns from PEA.

Despite the temporary hold on the internship training program in 2024, collaboration with PEA remained active in other areas. In December 2023, Grid*START* supported PEA's successful commissioning of a microgrid system on Koh Phaluai, an island in the southern Gulf of Thailand featuring 1 MW of photovoltaic capacity, a 750 kW/1,500 kWh battery energy storage system, and two 300 kW diesel generators, all managed with a centralized microgrid controller. This innovative system is designed to operate solely on renewable energy when conditions permit, providing reliable electrical service to island residents. This work is described in more detail in Appendix H3.

Waste-to-Bioenergy Conversion for Community PV-BioGrid

With APRESA funding, HNEI contracted Chiang Mai Rajabhat University, Thailand to conduct an assessment of small biomass systems as a firm power option in islanded settings. The study included a resource assessment of potential biomass feedstocks in Thailand, including urban solid wastes and agricultural residues and a technology assessment of available conversion systems. Based on the results, an anaerobic digestion system was selected to integrate into a grid-isolated community dependent largely on PV for electricity. The system has been installed at the University and after shake down testing, was integrated with the direct current microgrid system. Reports are being prepared to close out this effort.

OptiGrid

HNEI met with and planned a project with SGTech, Naresuan University focused on machine learning-driven optimization of battery energy storage systems (BESS) for Thai grid operations. Objectives include identifying effective use of BESS through design, installation, operation, and maintenance to ensure long life under Thai tropical conditions. Use cases for use of BESS to support and stabilize the Thai grid will be identified and studied. Based on the preliminary meetings under this award, SGTech was included in HNEI's APRISES 2023 proposal to ONR to fund the OptiGrid effort.

<u>Philippines</u>

Support to the USAID Energy Secure Philippines (ESP) Program

HNEI Grid*START*'s engagement with the Philippines power sector began in 2019 through collaboration with USAID Clean Power Asia by providing support to the Philippines Department of Energy (PDOE) for net energy metering (NEM) program development. This partnership expanded through APRESA and USAID Energy Secure Philippines (ESP) program funding, delivering technical support to the Philippines Energy Regulatory Commission (ERC), distribution utilities (DUs), and other relevant agencies. Key focus areas included developing "off-grid" NEM rules for rural areas and establishing a battery energy storage system (BESS) regulatory framework.

Throughout 2022 and 2023, HNEI delivered comprehensive off-grid NEM rules, BESS regulations, and capacity building for key stakeholders. In November 2023, Grid*START* delivered energy storage systems (ESS) training to PDOE, focusing on ESS costs and benefits in relation to the country's renewable energy goals of 35% by 2030 and 50% by 2040. The training addressed policy frameworks and institutional approaches for BESS implementation, while ensuring reliable and cost-effective electricity for both on- and off-grid systems.

In 2024, HNEI's scope expanded significantly to include an all-electric fishing boat design review, provincial utility capacity building, and an energy resiliency assessment for Camp Aguinaldo, the headquarters for the Armed Forces of the Philippines. The team conducted extensive site and stakeholder engagement across Manila, Bohol, Iloilo, and Siargao with local officials, provincial utilities, and key energy stakeholders to develop targeted solutions for provincial energy needs. This work is described in more detail in Appendix H4.

Indonesia

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

HNEI Grid*START* is providing technical support to USAID's Sustainable Energy for Indonesia's Advancing Resilience (SINAR) program, a five-year initiative supporting Indonesia's clean energy transition. The support encompasses capacity building in advanced energy systems including financing, procurement, planning, and operations. A key focus is improving the performance of energy utilities, particularly PT Perusahaan Listrik Negara (PLN), while strengthening the energy sector's institutional framework through enhanced procurement standards, cost recovery mechanisms, and modernized planning and operating practices.

In February 2022, HNEI delivered a three-day webinar on Hawaiʻi's renewable energy transformation to Indonesia's Directorate General of Electricity and Ministry of Energy and Mineral Resources. Building on this initial exchange, we conducted a three-day workshop on small island grid planning for PLN in Bali and a one-day webinar for the National Energy Council of Indonesia (Setjen DEN) in Jakarta in May 2023.

In February 2024, HNEI Grid*START* organized an extensive Smart Grid Benchmarking Study Tour in Hawaiʻi for Indonesian utility executives and stakeholders. The delegation visited both Oʻahu and Kauaʻi, participating in classroom training and field trips. The program included meetings with the Hawaiʻi Public Utilities Commission, State Energy Office, and Hawaiian Electric Company. On Kauaʻi, participants visited Kauaʻi Island Utility Cooperative (KIUC) facilities, examining hybrid PV and battery storage systems while learning about advanced metering infrastructure and operational technologies. This work is described in more detail in Appendix H5.

Laos

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 team resources limited due to other active support engagements across the Asia-Pacific region, HNEI Grid*START* plans to deliver in-person and remote training to EDL on these topics starting in 2025.

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

HNEI entered into a collaboration with Deloitte Consulting on October 27, 2022, as part of the USAID Southeast Asia Smart Power Program (SPP). This $40 million, five-year initiative aims to mobilize $2 billion in blended financing for clean energy infrastructure, supporting Southeast Asia's goal of achieving net-zero greenhouse gas emissions by 2050. HNEI's initial tasks centered on assisting Électricité du Laos (EDL) and the Lao Ministry of Energy and Mines (MEM) in three key areas: 1) enhancing power system resilience, 2) implementing demand-side management/demand response (DSM/DR) strategies, and 3) integrating variable renewable energy (VRE) resources into their transmission and distribution systems.

In 2023, HNEI Grid*START* delivered updated Feasibility Study Guidelines for wind, solar, and biomass energy projects in Laos, as well as an updated Grid Code incorporating interconnection standards for Inverter-Based Resources (IBRs). The team also conducted capacity building sessions for EDL and MEM staff on these topics. Continuing this support, in May 2024, HNEI virtually presented on IBR grid connection requirements at a workshop in Vientiane, Laos. The session, attended by approximately 30 key representatives from various organizations, highlighted applications and practices from the U.S., particularly Hawaiʻi. HNEI

Grid*START* is currently working with SPP to identify additional support needs for EDL and MEM, including strategy development and capacity building on hybrid (VRE and BESS) projects for cross-border energy trade with Cambodia and Thailand. This work is described in more detail in Appendix H6.

Cambodia

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

As a subcontractor to Deloitte Consulting for the USAID Southeast Asia Smart Power Program (SPP), HNEI is working to enhance grid resilience and renewable energy integration in Southeast Asia. This initiative involves long-term collaboration with Cambodia's Electricite de Cambodge (EdC) to manage high levels of variable renewable energy (VRE) and conducting regional capacity-building workshops for ASEAN Power System Operators (APSO). By sharing U.S. best practices, especially from Hawai‘i, we aim to strengthen utility capacity and promote renewable electricity trading.

In May 2024, HNEI Grid*START* conducted a workshop at EdC's headquarters in Phnom Penh, Cambodia, organized with USAID SPP and the Australian Department of Foreign Trade and Investment. This workshop enhanced Cambodian energy practitioners' understanding of VRE integration. In August 2024, another workshop was held during the APSO Annual Meeting in Manila, Philippines, focusing on improving VRE integration capabilities among ASEAN Member States. This work is described in more detail in Appendix H7.

Pacific Island Countries (PICs)

Renewable Energy Regulatory and Technical Support for Palau

HNEI is providing wide-ranging technical and regulatory/policy support to Palau's Energy and Water Administration (PEWA) and the Palau Public Utilities Corporation (PPUC) in three key areas: 1) energy regulatory frameworks, 2) grid modeling, and 3) renewable generation interconnection requirements and streamlined interconnection processing. Following a technical and financial analysis of PPUC's grid operations in October 2023, Grid*START* delivered new distributed generation interconnection requirements (i.e. a grid code), which PEWA adopted in February 2024. The team also delivered a three-day renewable energy integration training in Koror in June 2024.

To enhance support for Palau, HNEI met with the Asian Development Bank (ADB) in Manila during June and August 2024 to define collaborative opportunities. Additionally, Grid*START* launched a partnering arrangement with Okinawa Enetech and the Japan International Cooperation Agency (JICA) to coordinate and jointly deliver elements of their respective technical support for renewable energy integration in Palau. This work is described in more detail in Appendix H8.

Renewable Energy Regulatory and Technical Support for the Cook Islands

HNEI Grid*START* is providing technical and regulatory support to Te Aponga Uira (TAU), the government-owned electric utility of the Cook Islands. This collaboration began in September 2023 with a one-day training program in Honolulu for TAU's senior management and a board member, sharing Hawai‘i's energy transition experiences.

In July 2024, we conducted extensive capacity building sessions on Rarotonga, meeting with TAU management, board members, and Prime Minister Mark Brown. The presentations covered Hawai‘i's energy transitions, battery storage implementation case studies from Pacific Island Countries and Kaua‘i, and potential clean energy scenarios for Rarotonga.

Building on these engagements, HNEI continues to support the Cook Islands' clean energy transition through distribution feeder analysis, customer program development, utility financial planning, and renewable energy project procurement. Following the July 2024 visit, Grid*START* has continued to support TAU on key needs, such as distribution feeder analysis to determine the "hosting capacity" for distributed PV, and strategic measures to support and improve utility financial integrity. This work is described in more detail in Appendix H9.

Renewable Energy Regulatory and Technical Support for Yap State, Micronesia

HNEI Grid*START*, through APRESA funding and in partnership with the Pacific Power Association (PPA), is providing technical and regulatory support to the Yap State Public Service Corporation (YSPSC) in the Federated States of Micronesia. This collaboration builds on our involvement with PPA since 2023, when the team delivered invited presentations at PPA's 30th annual conference in Saipan.

In October 2024, HNEI conducted its first training at YSPSC's offices, delivering a two-day program covering Hawaiʻi's clean energy transition, variable renewable energy (VRE) management, grid interconnection standards, energy storage, electric vehicles, climate adaptation, and renewable energy procurement. The team provided hands-on training with its internally developed *Generation Mix Resource Modeling Tool* and conducted facility site visits to identify further support needs. Grid*START* plans to continue its support to YSPSC in 2025 and expand similar training programs to other Pacific region utilities under its partnership with PPA. This work is described in more detail in Appendix H10.

<u>Southeast Asia</u>

Sustainable Aviation Fuel (SAF) Production

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

Additionally, APRESA funding contributed to a sustainable aviation fuel workshop in Bangkok, Thailand in May 2023, which was organized by the Federal Aviation Administration (FAA), the U.S. Trade Development Agency, the National Energy Technology Center of Thailand, and HNEI. A second workshop was held in Bali, Indonesia in July 2024 co-organized by the FAA through their Aviation Sustainability Center (ASCENT), the Indonesian Directorate General for Civil Aviation, the National Energy Technology Center of Thailand, and HNEI. The workshops' goals were to share information on SAF developments in the region and to identify barriers to implementing SAF value chains spanning feedstock production to end use. Participants from various Asia-Pacific countries attended, representing civil aviation authorities, government policymakers, airlines, SAF feedstock producers, consumers, and technology providers, university researchers, and airport operators.

Oil Seed Production Analysis

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

Hawaiʻi's state tree, kukui (*Aleurites moluccannus*, or candlenut), bears nuts that are roughly 40% shell and 60% fleshy seed, the latter containing ~60% oil. Although commonly found in Hawaiʻi and across the Indo-Pacific region, little work has been done to understand kukui productivity and management. Utilizing APRESA funding, a review of the scientific literature is underway to provide a summary of the current knowledge and identify opportunities of exploration.

Funding Source: Office of Naval Research

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

Last Updated: November 2024

H2: Saigon Energy Hub (SEHub) Support

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

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

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

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

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

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

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

Six of the eight energy-related workshops have been conducted. The workshop topics covered carbon credits, offshore wind power, legal framework regarding energy savings, energy management, integrated infrastructure and transit oriented development, and geographic information system (GIS) as an effective urban management tool. To date, this workshop series has spanned 22 hours with 11 speakers and 260 participants (online and in-person). Participants have represented a range of stakeholders: researchers, technology associations, business owners, and policy makers

The last two workshops are planned for early 2025.

Funding Source: Office of Naval Research

Contact: Richard Rocheleau, rochelea@hawaii.edu; Eileen Peppard, epeppard@hawaii.edu

Last Updated: November 2024

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*) is providing capacity building and technical support to Provincial Electricity Authority of Thailand (PEA). As Thailand's primary distribution grid operator serving 74 of 77 provinces, PEA is advancing renewable energy integration through various initiatives. HNEI Grid*START* developed a capacity building program focused on renewable energy grid integration, smart grid technologies, microgrid assessment and design, and development of advanced electric vehicle (EV) charging applications. Beyond training programs, HNEI's support extends to technical assistance for PEA's microgrid development, particularly the commissioning of a microgrid on Koh Phaluai island in the Gulf of Thailand.

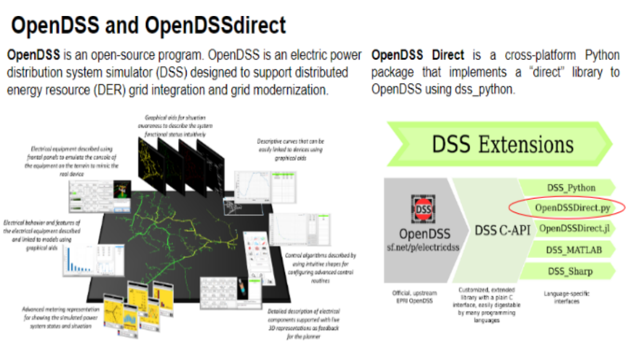


Figure 1. Sample of the teaching materials.

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

PROJECT STATUS/RESULTS: Following COVID-19 travel restrictions in 2020-2021, HNEI Grid*START* successfully hosted two classes of PEA engineers in 2022, focusing on advanced energy technologies and applications. The interns engaged in various mini projects, including virtual power plant dispatch optimization, EV energy consumption estimation, PV hosting capacity assessment, and microgrid system design using the XENDEE platform. These hands-on projects leveraged Grid*START*'s expertise in distributed energy resources, advanced EV charging, and smart grid technologies.

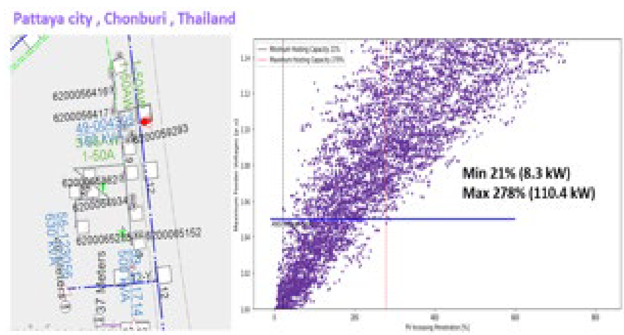


Figure 2. PV hosting capacity simulation on a PEA distribution feeder.

HNEI's hands-on technical assistance to PEA continued in December 2023, through its on-site support for PEA's commissioning of its microgrid on Koh Phaluai, an island in southern Thailand. This innovative system integrates 1 MW of PV, a 750 kW/1,500 kWh battery energy storage system (BESS), and two 300 kW diesel generators with a microgrid control system to provide utility electrical service to the residents of the island. The system is designed to operate without diesel generators when there is sufficient solar and BESS energy available to serve the load. While the internship program offered by HNEI Grid*START* was temporarily paused in 2023 and 2024, plans are well underway to host a new class of PEA interns in February 2025. This internship class will advance the understanding and know-how of PEA engineers in conducting techno-economic analysis necessary to assess and develop optimal microgrid configurations, and design and test microgrid controls for system operation of an actual planned PEA microgrid site in Thailand.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

H4: Support to the USAID Energy Secure Philippines (ESP) Program

OBJECTIVE AND SIGNIFICANCE: HNEI's Grid System Technologies Advanced Research Team (Grid*START*), under contract with the Research Triangle Institute (RTI), is delivering technical and regulatory support to the USAID-funded Energy Secure Philippines (ESP) Program, Philippines Energy Regulatory Commission (ERC), and Philippines Department of Energy (DOE). This support builds on previous collaborations with USAID Clean Power Asia utilizing APRESA funding.

BACKGROUND: The $34 million ESP Program aims to advance economic growth and energy sector resilience by mobilizing $750 million in private investment for 500 megawatts of additional generation capacity. In 2022 and 2023, HNEI's support of ESP included assisting in the development of comprehensive off-grid net energy metering (NEM) rules, developing and drafting a framework and regulations for battery energy storage systems, and providing capacity building for the ERC, DOE and distribution utilities (DUs) on various topics including microgrids, resiliency and energy storage.

Figure 1. AFP Camp Aguinaldo, Quezon City, Metro Manila, Philippines.

PROJECT STATUS/RESULTS: While in Manila presenting at the Asia Clean Energy Forum (ACEF) in early June 2024, HNEI Grid*START* met with its counterparts from RTI to discuss refinements to our ESP scope of work (SOW). Specifically, the parties discussed expanding the previous scope to include: 1) a design review for an electric-powered fishing boat; 2) in-person training sessions/presentations for select DUs and local government units (LGUs); 3) training on renewable energy use and power system resiliency for the Siargao Women's Center; 4) assessing the power distribution system of Siargao Electric Cooperative (SIARELCO); and 5) an assessment of and conceptual strategies for improving power system resiliency of the Armed Forces Philippines (AFP) General Headquarters at Camp Aguinaldo.

In June 2024, HNEI returned to the Philippines for site visits to the provinces covered by the expanded SOW and to meet with key energy stakeholders (e.g., DUs, LGUs) in Manila, Bohol, Iloilo, and Siargao. Some of the local officials with whom Grid*START* met during the site visits included the Mayor of Baclayon, Mayor and former Mayor of Del Carmen, Governor and a Provincial Board Member of Iloilo, and representatives of various DUs.

Discussions to build alignment on the expanded SOW with RTI continued through August 2024 when, while in Manila presenting at a USAID capacity building workshop for ASEAN power system operators, we participated in additional meetings with a representative from the Siargao Women's Center and AFP representatives at Camp Aguinaldo. A contract modification reflecting the expanded SOW was executed shortly thereafter in September 2024, with the period of performance extended through October 2025.

Pursuant to the modified SOW, HNEI Grid*START* delivered two in-person training sessions in Iloilo in November 2024: one for the MORE Electric and Power Corporation, and the second for the LGU there. Work on the remaining deliverables in the expanded SOW also began in late 2024 and is scheduled to continue into late 2025, including development of an energy resiliency risk assessment framework for the Philippines DOE and AFP.

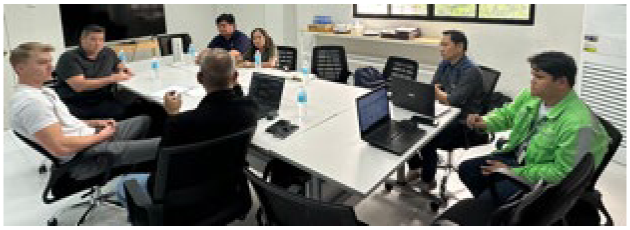


Figure 2. HNEI Discussing Capacity Building Support with MORE Electric Power Corporation on Iloilo.

Funding Source: USAID ESP Program; Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

Hawai‘i Natural Energy Institute Research Highlights

Appendix H: International

H5: USAID Sustainable Energy for Indonesia’s Advancing Resilience Program

OBJECTIVE AND SIGNIFICANCE: HNEI’s Grid System Technologies Advanced Research Team (Grid*START*) has partnered with Tetra Tech ES to support USAID’s Sustainable Energy for Indonesia’s Advancing Resilience (SINAR) program. The initiative aims to accelerate advanced energy development, enhance utility performance, implement transparent procurement practices, and strengthen the energy sector’s institutional framework in Indonesia.

BACKGROUND: Despite Indonesia’s abundant renewable energy (RE) resources, their utilization remains limited due to the country’s heavy reliance on fossil fuels and limited experience with RE integration. In recent years, Perusahaan Listrik Negara (PLN), Indonesia’s government-owned power distribution company, has prioritize de-dieselization and RE adoption as crucial elements of the nation’s clean energy transition. Through the SINAR partnership, HNEI Grid*START* is providing wide-ranging RE capacity building support to facilitate this transformation.

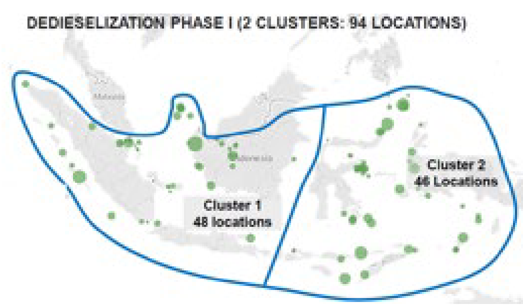


Figure 1. Planned de-dieselization in Indonesia.

PROJECT STATUS/RESULTS: In February 2022, HNEI conducted a three-day webinar on Hawai‘i’s RE transformation for Indonesia’s Directorate General of Electricity (DGE) and Ministry of Energy and Mineral Resources (MEMR). In May 2023, HNEI also conducted training for Setjen DEN (the National Energy Council of Indonesia) in Jakarta, as well as a three-day workshop on small island grid planning for PLN in Bali.

Building on discussions with key Indonesian energy stakeholders in 2023, Grid*START* coordinated and hosted a Hawai‘i Smart Grid Benchmarking Study Tour in February 2024, wherein a delegation of Indonesian utility executives and stakeholders visited O‘ahu and Kaua‘i to learn more about Hawai‘i’s RE transition. On O‘ahu, HNEI conducted classroom and in-the-field training on RE integration and coordinated meetings with the Hawai‘i Public Utilities Commission (PUC), State Energy Office, and Hawaiian Electric Company.

Figure 2. Indonesian delegates at Hawai‘i PUC.

Grid*START* coordinated visits with the Kaua‘i Island Utility Cooperative (KIUC), which provided further classroom training and also hosted visits to various KIUC facilities, including field trips to: KIUC’s Kapaia Power Station, which features a General Electric combustion turbine that has been modified to also operate as a synchronous condenser; Tesla’s hybrid PV + battery energy storage system (BESS) plant; and KIUC’s Port Allen control center. Throughout the study tour, the PLN delegation gained valuable insights into Hawai‘i’s RE strategies, innovations, regulations, and infrastructure.

Figure 3. SINAR’s Visit to KIUC on Kaua‘i.

Discussions with SINAR regarding future capacity building opportunities are ongoing, with a present focus on a planned internship at HNEI for PLN engineers in 2025.

Funding Source: USAID SINAR Program; Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

Hawaiʻi Natural Energy Institute Research Highlights

Appendix H: International

H6: USAID Southeast Asia's Smart Power Program – Laos

OBJECTIVE AND SIGNIFICANCE: HNEI's Grid System Technologies Advanced Research Team (Grid*START*) entered into a collaboration with Deloitte Consulting (Deloitte), the prime contractor for the USAID Southeast Asia Smart Power Program (SPP), in October 2022. This $40 million, five-year initiative aims to mobilize $2 billion in blended financing for clean energy infrastructure in Southeast Asia. The program's goal is to drive economic growth and development by creating secure, market-oriented, and environmentally responsible energy sectors, ultimately helping the region achieve net-zero greenhouse gas emissions by 2050. HNEI's role focuses on supporting Électricité du Laos (EDL) and the Lao Ministry of Energy and Mines (MEM) in enhancing power system resilience, implementing demand-side management/demand response (DSM/DR) strategies, and integrating variable renewable energy (VRE) resources.

Figure 1. Abstract of Laos map.

BACKGROUND: USAID SPP builds upon USAID's previous Clean Power Asia (CPA) program, under which HNEI delivered both collaborative (APRESA-funded) and CPA-funded support over the prior four years, expanding its scope to increase energy capacity, clean energy investments, and regional energy trade. The program leverages bilateral and multilateral partnerships, supports regional initiatives, accelerates cross-border interconnection, and establishes training centers for energy practitioners to develop solutions that enable Southeast Asian countries to become self-reliant and achieve their sustainable development aspirations.

HNEI Grid*START* and USAID SPP anticipate further collaboration opportunities across various task areas, including utility modernization, DSM/DR, energy innovation and emerging trends, competitive procurement, power trade, and grid integration.

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

In May 2024, HNEI Grid*START* virtually presented IBRs grid connection requirements and their applications at a capacity building workshop conducted in Vientiane, Laos. Approximately 30 key institutional representatives participated in the workshop, including the Japan-U.S.-Mekong Power Partnership (JUMPP) Technical Advisory Group, JUMPP workstream coordinators, EDL's Technical Working Group for Developing Rooftop Solar Installation and Management Regulations and Requirements, and relevant EDL departments and divisions.

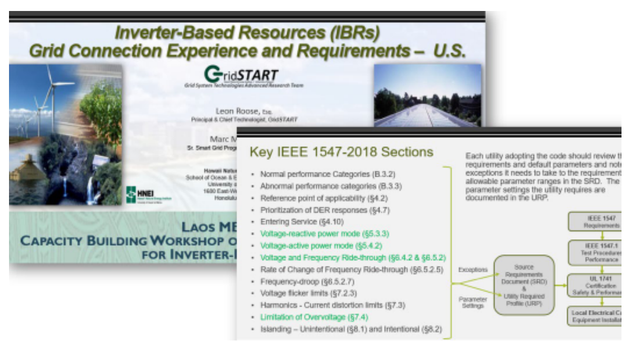


Figure 2. Portion of slides presented at the capacity building workshop in May 2024 in Vientiane, Laos.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

H7: USAID Southeast Asia's Smart Power Program – Cambodia

<u>OBJECTIVE AND SIGNIFICANCE</u>: HNEI's Grid System Technologies Advanced Research Team (Grid*START*), working as a subcontractor to Deloitte Consulting LLP (Deloitte), is supporting the implementation of the USAID Southeast Asia Smart Power Program (SPP) to enhance grid resilience and renewable energy integration across Southeast Asia. This project focuses on two key work streams: 1) a long-term engagement with the national power utility of Cambodia, Electricite de Cambodge (EdC) to manage high levels of variable renewable energy (VRE) penetration and 2) a regional capacity-building workshop for ASEAN Power System Operators (APSO). By transferring U.S. best practices, particularly from Hawaiʻi, HNEI aims to bolster utility capacity and facilitate increased renewable electricity trading, supporting development goals and modernizing regional power grids.

<u>BACKGROUND</u>: USAID SPP, a $40 million, five-year initiative, succeeds the Clean Power Asia (CPA) program, under which HNEI Grid*START* provided both collaborative (APRESA-funded) and CPA-funded support to Laos' energy sector. SPP aims to transform Southeast Asian energy sectors, mobilizing $2 billion in blended financing for clean energy infrastructure to help achieve the region's goal of net-zero emissions by 2050. The program expands energy capacity, increases clean energy investments, and enhances regional energy trade. It leverages partnerships to accelerate cross-border power trade and establish energy practitioner training centers. In 2023, we collaborated with SPP to deliver updated Feasibility Study Guidelines, a Grid Code, and interconnection standards for Laos, alongside capacity-building sessions. HNEI continues supporting SPP through its collaboration with Deloitte.

<u>PROJECT STATUS/RESULTS</u>: In May 2024, HNEI Grid*START* delivered a capacity-building workshop at EdC's headquarters in Phnom Penh, Cambodia. Organized with USAID SPP and the Australian Department of Foreign Trade and Investment, the workshop enhanced Cambodian energy practitioners' understanding of VRE integration. The workshop, attended by 40 key institutions' representatives, covered critical topics such as power systems coordination and flexible resources. A second capacity-building visit to EdC is being planned for early 2025.

Figure 1. HNEI at the EdC Capacity Building workshop in Phnom Penh, Cambodia.

In August 2024, Grid*START* conducted another workshop in conjunction with the APSO Annual Meeting in Manila, Philippines. Hosted by the Manila Electric Company and the Philippines Department of Energy, the two one-day sessions aimed to improve the capabilities of project developers, production planners, and grid operators in integrating VRE into national grids and facilitating green power trade. Participants from all ten ASEAN Member States engaged in discussions on leading practices, innovative designs, and strategies for enhancing grid resiliency and operational harmonization across the region.

Figure 2. HNEI speaking at the APSO Meeting in Manila, Philippines.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

Hawaiʻi Natural Energy Institute Research Highlights

Appendix H: International

H8: Renewable Energy Regulatory and Technical Support for Palau

OBJECTIVE AND SIGNIFICANCE: Under funding of the Asia Pacific Regional Energy System Assessment (APRESA) grant from the Office of Naval Research, HNEI's Grid System Technologies Advanced Research Team (Grid*START*) is providing technical and regulatory/policy support to the Republic of Palau. Particularly, HNEI is supporting Palau's Energy and Water Administration (PEWA) and Public Utilities Corporation (PPUC) in implementing the country's clean energy transition.

BACKGROUND: In 2022, Palau increased its renewable energy (RE) target from 20% by 2020 to 100% by 2050. The ability to secure financing for major RE projects from international funding sources is key to enabling the achievement of Palau's ambitious RE goals. For example, in 2023, a new 15.3 MW solar photovoltaic (PV) and 12.9 MWh battery energy storage system (BESS) project in Palau funded by foreign direct investment became the largest of its kind in the Western Pacific region.

Figure 1. PV arrays at Palau's SPEC PV+BESS plant.

Additional RE projects are already underway or being planned, including additional utility-scale BESS and substantial customer-sited rooftop PV rollouts. This unprecedented and increasing penetration of inverter-based resources (IBRs) on the PPUC power grid has given rise to significant technical and regulatory challenges in the areas of grid integration and operations, as well as rooftop PV program/tariff design.

PROJECT STATUS/RESULTS: In September 2023, at PEWA's request, HNEI hosted a three-day training program in Honolulu for PEWA and PPUC staff on issues relevant to Palau's energy transition. Discussions on further support to Palau continued through October 2023, when at PEWA's request, Grid*START* performed a high-level technical and financial analysis of PPUC's grid operations with both existing and planned utility-scale and customer-sited PV generation, including projected levels of future excess energy curtailment and energy shifting (i.e., BESS) needs. In February 2024, we developed and delivered a new grid code for Palau, which includes updated requirements for the interconnection of IBRs and has been adopted by PEWA. In June 2024, Grid*START* conducted a three-day in-person training at PPUC's offices in Koror for PPUC and PEWA staff on a range of RE integration topics.

Figure 2. Renewable energy capacity building at PPUC.

In October 2024, HNEI delivered in-person training in Koror on the newly adopted Palau grid code, including streamlined/online application and review processes for distributed rooftop PV interconnections. The team remains actively engaged in the following technical and regulatory support to PEWA and PPUC:

- Developing a "User's Handbook" to assist the PPUC in its use of the newly adopted grid code and streamlined/online application and review processes for rooftop PV interconnections;
- Designing new programs/tariffs for customer-sited PV/BESS systems;
- Hosting capacity analysis to integrate more RE, including building new models of the PPUC grid using DIgSILENT and SAint software; and
- Capacity building on system planning methods, including training on various grid modeling tools.

Figure 3. Distribution feeders on Malakal Island, Palau.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

H9: Renewable Energy Regulatory and Technical Support for the Cook Islands

OBJECTIVE AND SIGNIFICANCE: Under funding of the Asia Pacific Regional Energy System Assessment (APRESA) grant from the Office of Naval Research, HNEI's Grid System Technologies Advanced Research Team (Grid*START*) is providing technical and regulatory/policy support to Te Aponga Uira (TAU). TAU serves as the government-owned electric utility on Rarotonga, the capital of the Cook Islands nation in the South Pacific.

Figure 1. Muri Lagoon on Rarotonga.

BACKGROUND: The Cook Islands Economic Development Strategy 2030 has a renewable energy (RE) target of 60% by 2030. TAU on Rarotonga has approximately 5,000 customers and is responsible for approximately 90% of the Cook Islands' electricity generation. The power grid on Rarotonga serves a peak demand of approximately 5.5 megawatts (MW). Approximately 85% of the energy comes from diesel generation, while the remaining 15% is generated from biomass and solar photovoltaics (PV), including a significant number of rooftop PV systems owned by customers who are credited for the electricity that they export to the grid. In addition, several utility-scale PV and battery energy storage system (BESS) projects on Rarotonga have been and are being financed by international funding sources.

Figure 2. Te Mana o Te Ra PV + BESS project (1 MW, 5.6 MWh) at the Rarotonga International Airport.

Once placed in service, the projects currently in the queue will increase TAU's RE percentage to approximately 30%. TAU also provides technical support to smaller power systems on the Pa Enua (Outer Islands) and is wholly owned by the Cook Islands Investment Corporation (CIIC).

PROJECT STATUS/RESULTS: In September 2023, HNEI hosted a one-day training program in Honolulu for senior management and a board member of TAU, focusing on experiences and lessons learned from Hawaiʻi's energy transition. Discussions between Grid*START* and TAU on potential topics for additional support continued over the following months and, in July 2024, HNEI conducted a week of capacity building presentations and meetings on Rarotonga with TAU management, the TAU and CIIC boards of directors, and Prime Minister Mark Brown.

Figure 3. HNEI and TAU leadership with Prime Minister Brown.

Building on its discussions with TAU, HNEI Grid*START* is continuing to support the Cook Islands' clean energy transition in key areas including:

- Distribution feeder analysis to determine the "hosting capacity" for distributed PV;
- Sharing Hawaiʻi's experience with customer programs to enable customer choice;
- Strategic measures to support and improve utility financial integrity; and
- Planning for and procurement of future RE projects.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

H10: Renewable Energy Regulatory and Technical Support for Yap State, Micronesia

OBJECTIVE AND SIGNIFICANCE: In partnership with the Pacific Power Association (PPA) and under funding of the Asia Pacific Regional Energy System Assessment (APRESA) grant from the Office of Naval Research, HNEI's Grid System Technologies Advanced Research Team (Grid*START*) is providing technical and regulatory/policy support to the Yap State Public Service Corporation (YSPSC) in the Federated States of Micronesia (FSM).

BACKGROUND: PPA is an inter-governmental agency whose objective is to improve the quality of power in the Pacific region through a cooperative effort among the utilities, private sector, and regional aid donors. HNEI has been working with PPA since 2023, when we participated as an invited presenter at PPA's 30th annual conference in Saipan. Over the past year, Grid*START* has worked with PPA to shape a partnership to deliver much needed capacity building to PPA's member utilities.

Figure 1. PPA's 30th Annual Conference in Saipan.

YSPSC is a state-owned utility that provides water, electricity, and sewer services to Yap's main island (Yap Proper), as well as the state's outer islands. The peak demand on Yap Proper is approximately 1.9 MW and is served by approximately 11 MW of installed capacity. Approximately 10% of Yap's installed capacity comes from renewable energy (RE) sources, such as solar photovoltaic (PV) and wind. This includes both utility-scale projects funded by entities, such as the Asian Development Bank, and smaller systems installed by customers who benefit from net energy metering (NEM) tariffs. Significant increases in variable renewable energy (VRE) penetration, battery energy storage systems (BESS), and electric vehicles (EVs) are expected on Yap in the near future, including projects procured on a bundled basis by the larger FSM government, and owned/operated by YSPSC. Significant new load demand from U.S. Department of Defense facilities under construction is anticipated.

PROJECT STATUS/RESULTS: The first training provided by HNEI Grid*START* under its partnership with PPA was conducted at YSPSC's offices in October 2024. The training consisted of two full days of slide presentations and discussions on stated topics of interest for YSPSC including:

- Hawaiʻi's clean energy transition;
- Managing high VRE penetrations;
- Updated grid interconnection standards;
- BESS and EVs;
- Climate adaptation and resilience; and
- Competitive procurements for RE projects.

HNEI also provided its internally developed *Generation Mix Resource Modeling Tool* to YSPSC personnel and trained them on its use. The team visited the island's power generation and distribution facilities and engaged in further discussion with YSPC's management to identify potential avenues for future follow-on support, which Grid*START* plans to deliver to YSPSC in 2025. HNEI also plans to conduct additional trainings for other Pacific region utilities under its partnership with PPA.

Funding Source: Office of Naval Research

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

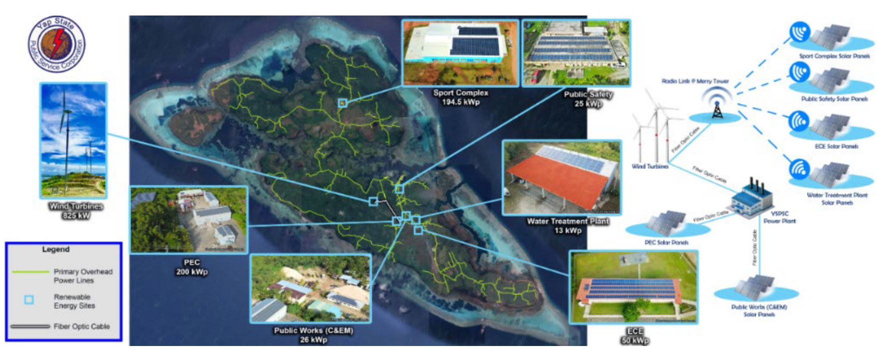


Figure 2. VRE installations on Yap Proper.

H11: Energy Security and Resilience in the Caribbean Islands

OBJECTIVE AND SIGNIFICANCE: In February 2023, HNEI's Grid System Technologies Advanced Research Team (Grid*START*) was contracted by Deloitte & Touche LLP (Deloitte) to deliver technical assistance under the U.S. Department of State's (DOS) Power Sector Program Technical Assistance to Support the Partnership to Address Climate Change 2030 (PACC 2030). This initiative serves as the framework for U.S. government climate and clean energy engagement.

BACKGROUND: The Caribbean region faces significant energy challenges, with the highest dependency on imported oil for power generation and the highest average electricity prices in the Western Hemisphere.

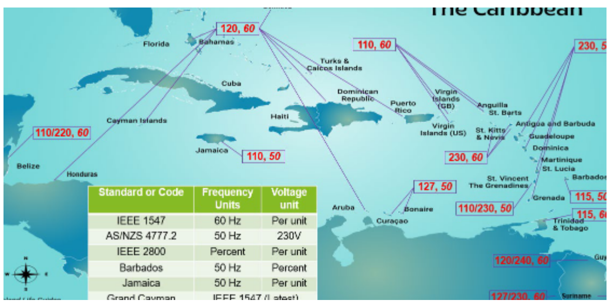


Figure 1. Caribbean electricity voltages and frequencies (Excerpted from Island Life Guides).

This situation creates vulnerability to global supply shocks and unreliable electricity service. Following years of energy engagement under the Caribbean Energy Security Initiative (CESI), the Biden-Harris Administration announced PACC 2030 in June 2022 during the U.S.-hosted Summit of the Americas. PAC 2030 focuses on enhancing regional energy security through initiatives including geothermal development in the Dominican Republic, building regulatory capacity, and strengthening technical capabilities in renewable energy integration, electric mobility (e-mobility), and power system resilience.

PROJECT STATUS/RESULTS: HNEI is providing analytical and advisory services for various activities and deliverables including conducting multiple in-person and virtual regional regulatory training sessions for members of the Caribbean Electric Utility Services Corporation (CARILEC) and Organization of Caribbean Utility Regulators (OOCUR) and preparing technical reports on a variety of topics for Caribbean energy stakeholders.

HNEI Grid*START* has already delivered several of the trainings and reports outlined in its contract with Deloitte, including:

- Six days of virtual training on the integration of high penetrations of variable renewable energy (VRE) encompassing topics such as planning, operational design, power system management, grid codes and energy resource forecasting;
- Two days of in-person/hybrid training in Trinidad and Tobago on grid flexibility and procurement of grid services;
- Two reports on grid code recommendations, reliability benchmarks and criteria, and PV integration for Saint Kitts and Nevis; and
- A report on climate adaptation and resiliency for Trinidad and Tobago.


Figure 2. Homes destroyed by Hurricane Beryl in 2024.

HNEI continues its work to deliver on several PAC 2030 initiatives, including technical reports with recommendations for Jamaica Public Service (JPS) on clean energy transition needs, and further virtual regional regulatory training sessions for members of CARILEC and OOCUR. In October 2024, HNEI Grid*START* also facilitated the launch of DOS's new Caribbean Grid Code Accelerator initiative at CARILEC's annual conference in the Cayman Islands, which aims to support the development of a unified, flexible, resilient, and sustainable standard grid code template tailored to the unique needs of the countries in the Caribbean region. The Caribbean Grid Code Accelerator initiative will continue into 2025 with HNEI support.

Funding Source: U.S. Department of State

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

Hawaiʻi Natural Energy Institute Research Highlights

Appendix H: International

H12: USAID Papua New Guinea Electrification Partnership (PEP) Activity

O**BJECTIVE AND** **S****IGNIFICANCE**: HNEI's Grid System Technologies Advanced Research Team (Grid*START*) is providing technical assistance to Research Triangle Institute (RTI), the prime contractor implementing the United States Agency for International Development (USAID) Papua New Guinea (PNG) Electrification Partnership (PEP) Activity. This five-year project (2020-2025) partners with PNG's government to advance the country's self-reliance by helping achieve 70% population electricity access by 2030. Through expanding reliable and affordable electricity access, USAID-PEP aims to promote inclusive growth and community development throughout PNG.

Figure 1. PPL's main power systems in PNG, extracted from the PPL Diagnostic Assessment Report.

B**ACKGROUND**: USAID-PEP centers and coordinates its activities around four major objectives: 1) strengthen PNG Power Limited's (PPL) financial viability and operational efficiency, which focuses on building PPL's capacity to sustainably improve its profitability and performance; 2) develop viable off-grid electrification models, which focuses on supporting improvements in off-grid and mini-grid markets; 3) enhance PNG's energy regulator, which focuses on enhancing the capacity of the National Energy Authority (NEA) established in 2021; and 4) catalyze private investment for energy projects, which focuses on contributing financial support for the implementation of Objectives 1-3.

P**ROJECT** **S****TATUS/****R****ESULTS** Since 2021, HNEI has been instrumental in advancing USAID-PEP's objectives through various technical assistance initiatives. The team has strengthened PNG's regulatory framework through several key contributions: reviewing and proposing amendments to the NEA Act, providing detailed analysis of the draft PNG Off-Grid Regulation, and updating PNG's Electricity Industry Regulations. In the technical domain, HNEI Grid*START* has evaluated International Electrotechnical Commission (IEC) standards for rural electrification by PNG's National Institute of Standards and Industrial Technology (NISIT). The team has also conducted specialized training on Hybrid Optimization of Multiple Energy Resources (HOMER) grid modeling software while developing ten District and Provincial Energy Plans to support remote area electrification.

In May 2022, responding to USAID-PEP's request, Grid*START* supported NEA by reviewing and enhancing the Third-Party Access (TPA) Code and Grid Code for transmission-level interconnections. This work included developing and proposing interconnection standards for inverter-based resources (IBR) interconnected at the distribution level. The team then organized a four-day in-person workshop in November 2022 to address three key areas: the PNG Grid Code and distributed energy resource interconnections, the PNG TPA Code and technical regulations, and public consultation processes with NEA, PPL, and independent power producers. Throughout 2023, Grid*START* continued refining both the TPA Code and Grid Code, adding a significant section on Distributed Generating Unit Interconnection Standards Technical Requirements, which was then presented to the NEA Board of Directors. Following stakeholder feedback in 2024, HNEI participated in two public consultations on the draft Grid Code, which now awaits final adoption. Meanwhile, discussions continue with RTI regarding future support for USAID-PEP into 2025.

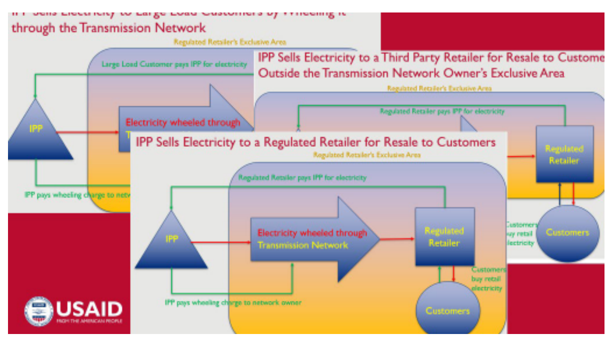


Figure 2. Slides illustrating NEA's TPA Code.

Funding Source: USAID-PEP

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024

H13: USAID Majuro Dock Resilient Power Strategy

OBJECTIVE AND SIGNIFICANCE: HNEI's Grid System Technologies Advanced Research Team (Grid*START*) was contracted by the U.S. Agency for International Development (USAID) through its prime contractor, DAI Global, LLC in collaboration with Pacific International, Inc. (PII), to design a reliable, resilient, cost-effective, and scalable power solution to support increases in the transshipment of skipjack tuna through a locally owned dock facility (Dock) on Majuro Atoll in the Republic of the Marshall Islands (RMI). Tuna transshipments though the Dock are essential not only to the global fishing industry, but also RMI's national economy.

Figure 1. HNEI and PII's Kramer family in Majuro, RMI.

BACKGROUND: Energy usage at the PII Dock is primarily a function of tuna-filled refrigerated container cooling loads, which are forecast to dramatically increase in step with tuna transshipment operations over the next decade. However, the electric service from the local electric utility, Marshalls Energy Company (MEC), is not reliable and its customers experience frequent power outages. In order to protect substantial perishable inventories, PII requires that it be able to serve 100% of its load via self-generation or other operational mechanisms when electric service from MEC is not available. HNEI Grid*START* was engaged to analyze the techno-economic feasibility and benefits and develop a strategy for phased upgrades to the current Dock energy system to enable it to operate both as a microgrid connected to the MEC electric system and as a stand-alone facility. The analysis included evaluations of various combinations of existing and potential renewable and thermal energy generation resources and energy storage capabilities.

PROJECT STATUS/RESULTS: As a foundational component of its analysis, HNEI projected hourly loads for the Dock at various stages of its expansion, including the addition of a planned 2,000 metric ton cold storage facility. Potential solutions to fill the gaps in PII's power and energy needs were evaluated utilizing the proprietary XENDEE Microgrid Decision Support Platform, a microgrid optimization planning tool that evaluates the resiliency and cost-effectiveness of microgrid energy systems. The microgrid simulations performed in connection with this project considered fixed costs, energy bill savings, and other variables (e.g., resiliency) to derive optimized microgrid designs, including optimized quantities of PV generation potentially including a battery energy storage system (BESS).

At a high level, the results indicate that there is an opportunity for PII to significantly reduce its operating costs and mitigate its business risks by maximizing self-generation, including solar photovoltaic (PV) panels on the roofs of its facilities, in lieu of relying upon the purchase of MEC-produced electrical energy. Additional measures such as the installation of a cold storage facility and/or more frequent transshipments of tuna off the Dock could reduce operating costs even further. Such cost reductions could improve RMI's competitiveness in relation to the foreign vessels that currently transfer their tuna inventories offshore in the Majuro lagoon (with little or no benefit to the local economy).

Figure 2. Purse seiner fishing vessel moored at PII Dock.

The results of Grid*START*'s analyses also appear to have caught the attention of international financing entities, which could potentially fund renewable energy investments at the Dock capable of achieving solar PV penetrations as high as 40% over the 25-year life of the project.

Funding Source: USAID

Contact: Leon Roose, lroose@hawaii.edu

Last Updated: November 2024