FINAL TECHNICAL REPORT

Asia Pacific Research Initiative for Sustainable Energy Systems 2023

Office of Naval Research

Grant Award Number N000142412397

July 1, 2024 through May 12, 2025

HNEI
Hawai‘i Natural Energy Institute
University of Hawai‘i at Mānoa

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Table of Contents

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EXECUTIVE SUMMARY

This report summarizes work conducted under Grant Award Number N000142412397, the Asia Pacific Research Initiative for Sustainable Energy Systems 2023 (APRISES23), funded by the Office of Naval Research (ONR) to the Hawaiʻi Natural Energy Institute (HNEI) of the University of Hawaiʻi at Mānoa (UH). The work conducted under APRISES23 was intended to comprise research, development, testing, and evaluation (RDT&E) over a range of technical areas. These included: Alternative Fuels including marine fuels and hydrogen, and Resilient Energy Systems including development and demonstration of novel technologies for advanced smart microgrids, resource adequacy studies for the Hawaiʻi electrical grids, and expansion of reliability and resilience efforts to the broader Asia Pacific region initiated under the Asia Pacific Regional Energy System Assessment (APRESA) program (ONR N00014-17-1-2923). We also proposed that Makai Ocean Engineering, under subcontract to the University of Hawaiʻi, continue their efforts to develop high-performance, low-cost heat exchangers. However, due to a work stop order on May 12, 2025, funds were expended only in the areas of hydrogen and grid technology. A brief summary of results by area follows.

Under the "Alternative Fuels" task, HNEI utilized APRISES23 funding to complete a control software overhaul of the hydrogen dispenser, replace the primary control board of the electrolyzer, and implement power monitoring systems. Additionally, the team responded to the loss of technical support from one of our partners and tackled key planning efforts for the shutdown and transfer of hydrogen station assets. Briefings, tours, community engagement, and public outreach activities were also carried out.

Under the "Resilient Energy Systems" task, HNEI built on prior work exploring distributed energy resources, grid-edge controls, and electric vehicle (EV) integration to improve grid performance and cost effectiveness. This research, conducted by HNEI's Grid System Technologies Advanced Research Team (Grid***START***), continued efforts to extend the bidirectional EV charging demonstration project into the residential context through technoeconomic analysis. A limited effort to provide technical support for island utilities in the Asia Pacific region, established under the APRESA program, also occurred with APRISES23-funded activities focused on the Cook Islands and Palau. This work centered on the application of advanced modeling tools and techniques, training workshops, and engagements with utilities and its energy regulators to strengthen host-country capabilities in system analysis, policy and regulation, and planning for small island grids in the context of maintaining secure energy systems during rapid energy transitions.

The bidirectional EV charging demonstration project at the University of Hawaiʻi at Mānoa includes two advanced bidirectional chargers with novel control algorithms developed to optimize EV charge/discharge cycles for cost savings, fleet management, and potential grid services. Under APRISES23, detailed technoeconomic modeling was applied to a representative residential community with a total household load of 400 kW and assumed participation of fifteen EVs. Seven scenarios were simulated under three time-of-use (TOU) rate structures, ranging from baseline operation to combinations of PV, stationary storage, smart charging, and bidirectional EV integration. Results showed that while unidirectional charging provided modest cost benefits, bidirectional charging coupled with PV resources consistently achieved the largest reductions in electricity costs, in some cases exceeding 20% monthly savings under TOU tariff conditions. These findings underscore the potential of flexible, intelligently managed EV charging to provide significant household economic benefits.

Funding under HNEI's APRESA program established the relationship framework for energy transition support and previous collaboration with Te Aponga Uira (TAU), the utility serving Rarotonga. Utilizing APRISES23 funds, HNEI introduced the Scenario Analysis Interface for Energy Systems (SAInt) modeling platform to TAU, facilitating its first integrated platform capable of production cost modeling combined with transmission and distribution power flow analytics. Preliminary scenario analyses evaluated the role of battery energy storage systems (BESS), demonstrating opportunities to reduce costs, limit curtailment of excess PV energy production, and use of storage as reserves.

In Palau, building on past work performed under APRESA, this award enabled the launch of a detailed PV hosting capacity study focused on the "Airport Feeder" of the Palau Public Utilities Corporation (PPUC) distribution system. This modeling effort provided a technical foundation for identifying integration limits and evaluating additional PV deployment scenarios.

This final report describes the research completed under each of these areas. Publications produced through these efforts are noted below and available on HNEI's website at https://www.hnei.hawaii.edu/publications/project-reports/aprises-23/.

HYDROGEN REFUELING TECHNOLOGY

The Hawai‘i Hydrogen Power Park (“Power Park”) was established in 2003 to support the U.S. Department of Energy’s (DOE) Technology Validation Program. The Power Park was funded by the DOE through the Department of Business, Economic Development and Tourism’s Strategic Industries Division (DBEDT), with the Hawai‘i Natural Energy Institute (HNEI) at the University of Hawai‘i serving as the implementing partner. This effort conducted engineering and economic validation of pre-commercial hydrogen technologies. Power Park Phase 1 systems included a commercial scale grid-connected alkaline electrolyzer interfaced with a gas storage system and a 5 kW proton exchange membrane (PEM) fuel cell located at the Hawai‘i Fuel Cell Test Facility (HFCTF) in Honolulu.

Power Park Phase 2 was proposed to expand the capabilities of the Power Park through the testing and validation of hydrogen fueling system technologies on the Big Island of Hawai‘i. In parallel, the Hawai‘i Volcanoes National Park (HAVO) had been selected for funding through the Advanced Transportation for Parks and Public Lands (ATPPL) program by the Department of Transportation (DOT) via the Department of Interior (DOI) to purchase two hydrogen-hybrid shuttle buses for tours of the park. The project was intended to support HAVO’s hydrogen fueling requirements leveraging additional investment from the State of Hawai‘i’s Hydrogen Investment Capital Special Fund (“Hydrogen Fund”). In its initial formulation, the Department of Defense (DOD), through the Kilauea Military Camp (KMC), offered to serve as the host site for the fueling infrastructure for the vehicles.

While initially targeted for installation at the HAVO site, concern about environmental issues in the National Park resulted in a site change to the Puna Geothermal site. In this configuration, support for the HAVO vehicles was to be provided by leveraging a hydrogen production system installed at the Puna Geothermal Ventures (PGV) power plant utilizing renewable electricity produced at the geothermal plant to produce electrolytic hydrogen. The hydrogen was to be delivered to HAVO by tube trailer and dispensed to the HAVO vehicles from a dispenser located at the KMC site.

In 2010, in response to Navy’s interest in the use of fuel cell vehicles to achieve higher vehicle efficiency and to lower fuel use, HNEI collaborated with the Naval Research Laboratory (NRL), proposing a collaborative project to DOE to investigate the potential for the intermittent operation of a grid-connected electrolyzer to produce hydrogen and provide grid services for large-scale electric grid applications. NRL served as the technical lead and overseer of the hydrogen production program with HNEI serving as the implementing partner. Ultimately, community concerns with the PGV site resulted in a final siting at the Natural Energy Laboratory Hawai‘i Authority (NELHA) site in Kona, Hawai‘i.

The PGV/NELHA hydrogen production system was procured under Award N00173-10-1-G037, P00001 through NRL. The stated objectives of the project were to optimize use of the electrolyzer and hydrogen storage system and utilize the hydrogen for transportation while also allowing greater penetration of variable renewable generation sources onto the grid, and to reduce barriers to the introduction of the hydrogen infrastructure. The variable hydrogen production was intended to support load leveling of the electricity produced by variable renewable energy sources such as wind, solar, and geothermal on the Big Island of Hawaiʻi. Hydrogen produced from the system was also intended to be used as a transportation fuel.

Under this agreement, HNEI conducted cyclic testing of the hydrogen production system at Powertech Labs, located in Vancouver, Canada, to characterize the dynamic response of the system. Following modification of the system controls, it was installed at NELHA on the Island of Hawaiʻi. Performance data under cyclic conditions was collected and reported jointly to ONR and DOE under the prior work.

In addition to conducting the research to characterize and control the variable load to provide grid services, additional goals included:

1. Support hydrogen vehicle demonstration projects on the Big Island of Hawaiʻi;
2. Conduct technical analysis of system and subsystem performance in a real-world environment; and
3. Document liability, insurance, and permitting issues and their resolutions.

As illustrated in Figure 1.1, the concept was to produce fuel cell grade hydrogen at NELHA to be delivered to the Mass Transit Agency (MTA) base yard in Hilo to support heavy-duty FCEBs operated by the MTA Hele-On public bus service. Three trailers each with a capacity of 105 kg were procured for transporting hydrogen between the production and fueling site. The trailers were certified by the Federal Transit Administration Department of Transportation for use on U.S. public roads.

Figure 1.1. Concept diagram of the transportation of hydrogen on the Big Island of Hawaiʻi.

These investments collectively supported not just capital deployment but also workforce development, operations, long-term resilience, and research activities within Hawai‘i’s unique island environment.

At the core of this project was Hawai‘i’s first public hydrogen fueling station, commissioned at NELHA. The station utilizes a Nel (formerly Proton Onsite) 65 kg/day PEM electrolyzer to produce ultra-pure hydrogen at 30 bar (440 psi). A Hydro-Pac compressor increases this pressure to 438 bar (6,352 psi), enabling storage in three DOT-certified trailers with a capacity of 105 kg each. Hydrogen fueling occurs at a nominal 350 bar (5,000 psi) through fully automated dispensers equipped with advanced safety interlocks and fail-safe mechanisms, supported by redundant underground piping and specialized interfaces designed specifically for these hydrogen transport trailers (Figures 1.2, 1.3, and 1.4). Early operations revealed critical lessons about control system responsiveness and software reliability, leading to a complete redevelopment of fueling control software and operational protocols—a process that granted Hawai‘i full technical autonomy over its hydrogen dispensing systems.

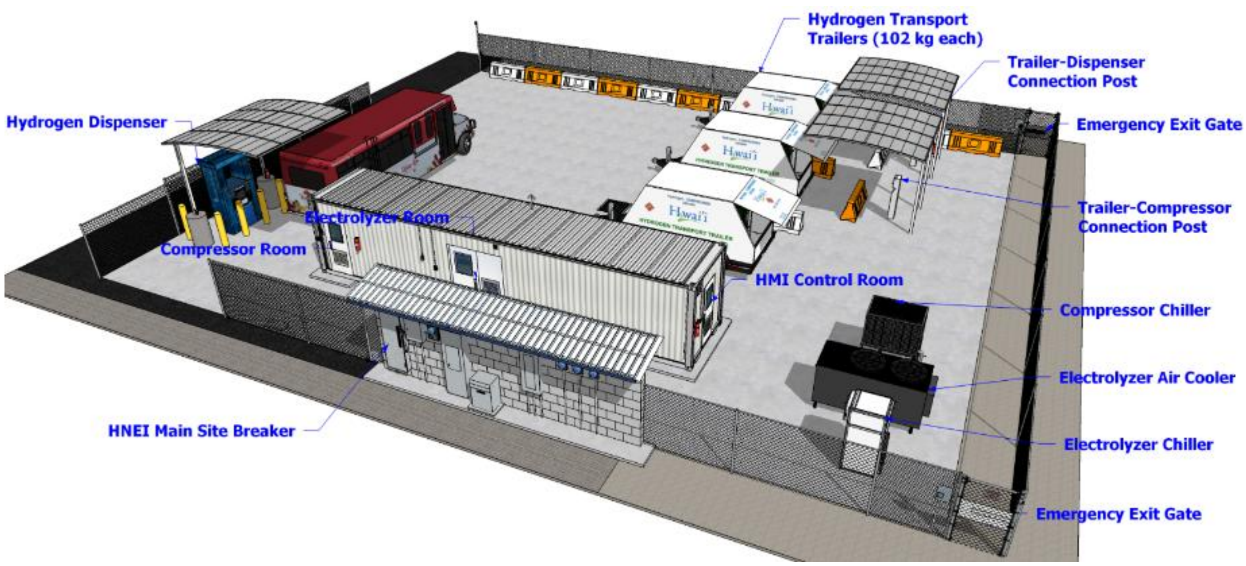

Figure 1.2. Major components of Hawai‘i’s first hydrogen fueling station at NELHA.

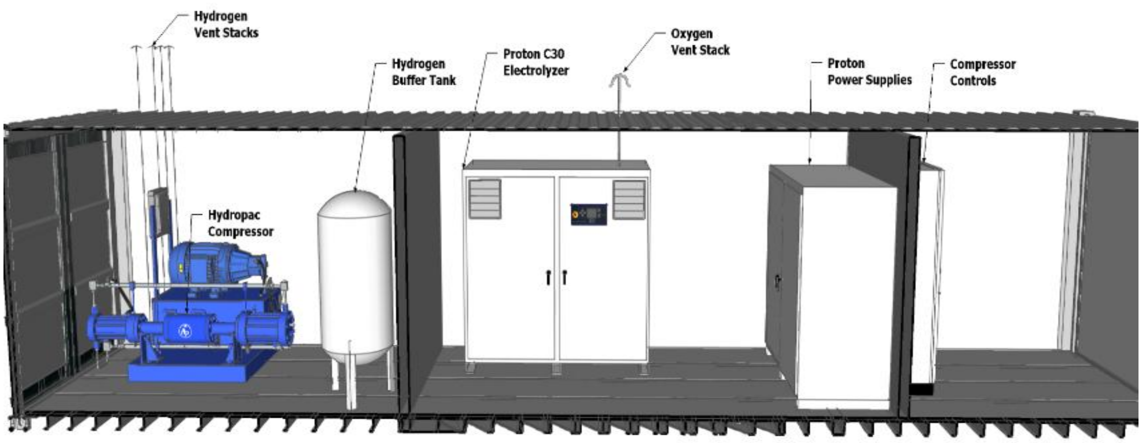

Figure 1.3. The components inside the shipping container.

Proton onsite C30 electrolyzer

Hydro-Pac compressor

Powertech/HNEI mobile hydrogen tube trailer

Figure 1.4. Process flow illustrating hydrogen being produced on site through water electrolysis and then compressed to 450 bar and stored in mobile hydrogen tube trailers.

During the initial bus deployment phase, HNEI played a critical role supporting U.S. Hybrid's startup and integration of the 21-passenger hydrogen fuel cell electric bus, resolving a range of technical challenges such as optimizing fuel cell battery charging, algorithms to allow safe charging at stoplights, mitigating DC-to-DC converter fuse failures through hardware and software improvements, and enhancing thermal management via increased radiator fan speeds at low bus speeds. Additional efforts included troubleshooting sensor interference, repairing drivetrain components, and addressing cooling system leaks, enabling the bus to enter reliable daily service routes where it demonstrated impressive performance metrics of approximately 1.2 kWh energy consumed per mile and 12.7 miles per kilogram of hydrogen over 145-mile runs.

The program also supported workforce training and public engagement through tours, workshops, and community events. HNEI supported the MTA's efforts to secure over $23 million in FTA Low/No Emission grants to acquire additional fuel cell buses and expand infrastructure.

Operating in close proximity to Hawai‘i's marine environment posed additional technical challenges. The team developed an aggressive program to address corrosion caused by the coastal salt-air atmosphere that included selecting corrosion-resistant materials and refining maintenance schedules.

In addition to station development, HNEI supported the retrofit and deployment of two fuel cell electric buses (FCEBs) in the County of Hawai‘i’s Hele-On fleet. The primary vehicle (Figures 1.5 and 1.6) is a 21-passenger ADA-compliant bus designed and converted by U.S. Hybrid, powered by dual 11 kWh lithium-ion batteries, a 200 kW drivetrain, and a 40 kW fuel cell (upgraded from the original 30 kW). This bus also integrates a 10 kW export power system capable of sustaining emergency AC power for up to 30 hours on a single hydrogen fill—an innovation enhancing community resilience in emergencies or extended power outages. The secondary platform is a 19-passenger bus originally intended to serve Hawai‘i Volcanoes National Park that was upgraded with a 90 kW Hyundai fuel cell and an expanded 33 kWh battery pack to enable service on Hawai‘i’s more challenging topographic routes.

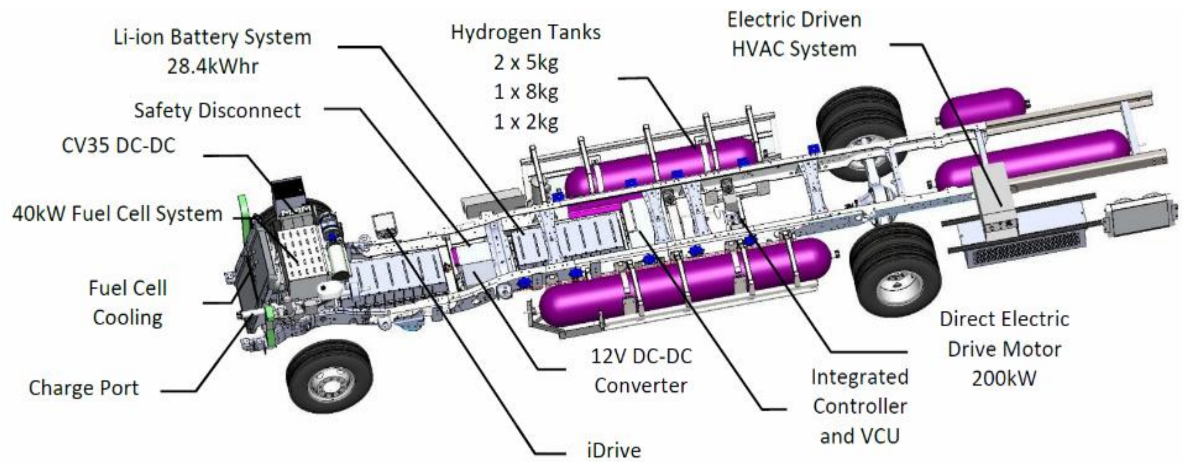

Figure 1.5. Components of a hydrogen fuel cell bus.

Figure 1.6. Hele-On Bus refueling at the 350 bar hydrogen dispenser.

Throughout the project, advanced data collection systems (Figure 1.7) captured data on bus operations and station performance. The data from this program is being used by Hawai‘i County for its strategic fleet planning and demonstrated the technical viability of hydrogen fueled transportation under real-world conditions that include varied terrain, climate, and logistical constraints.

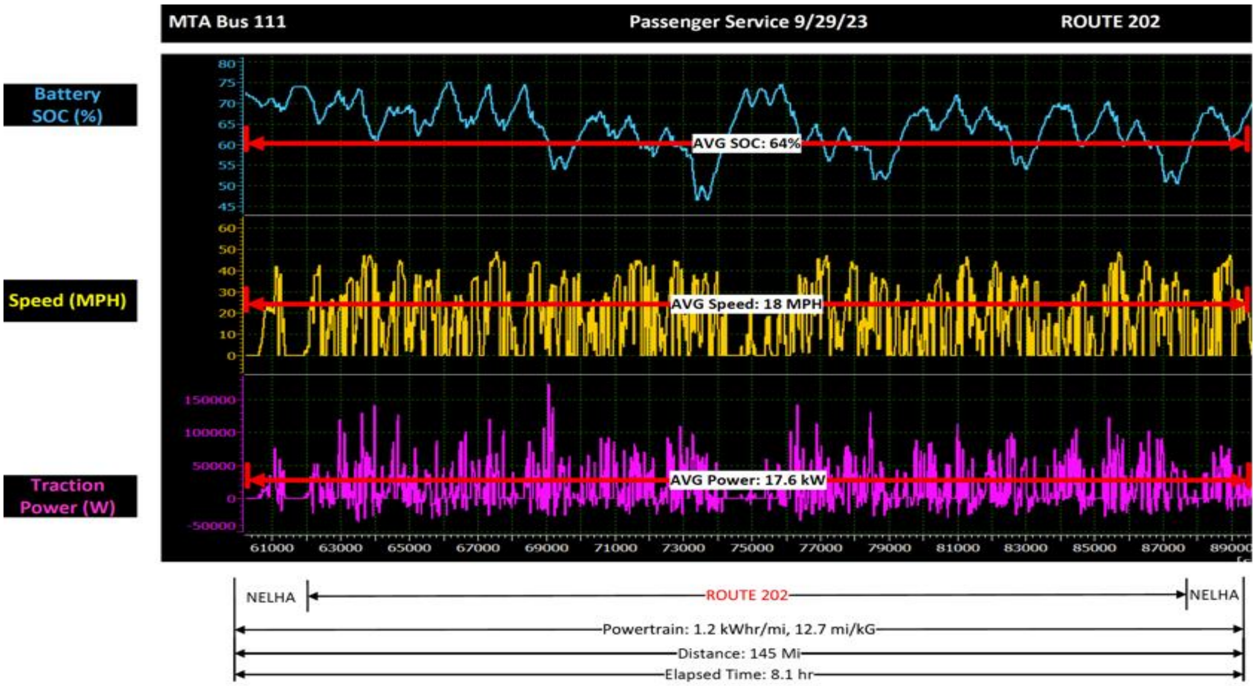

Figure 1.7. Telemetry data from the buses.

Beyond technological deployment, a core element of the program was workforce development. HNEI developed and delivered training modules tailored for bus operators, maintenance technicians, emergency responders, and fueling station staff. These programs combined classroom instruction, hands-on equipment familiarization, and emergency drills, building a robust, locally based cadre of hydrogen-qualified personnel poised to sustain and expand hydrogen transit operations.

Community and stakeholder engagement included tours (Figure 1.8), briefing sessions, public demonstrations, and educational programs enriching local understanding and support. A number of high-profile events, such as the "Meet the Bus" launch and participation in DOE's H2 Twin Cities initiative, served to connect Hawai'i's hydrogen experience to national and international clean energy movements. Academic collaborations fostered knowledge exchange and amplified the program's contributions through peer-reviewed scientific publications addressing corrosion and hydrogen integration challenges in marine environments.

Figure 1.8. Tour of the hydrogen station.

Recognizing the strategic importance of resilience, the project advanced innovative uses of hydrogen transit technology for emergency preparedness. The export power capability embedded in the buses is able to provide critical backup power for critical community needs during grid failures—offering an additional layer of service and underscoring hydrogen's versatility beyond transportation. Additionally, the program maintained comprehensive hydrogen station operational and safety documentation, including the operations manual, safety management plan, emergency response plan, standard operating procedures, and hazardous material and waste management program to ensure safe and reliable station and fleet.

Approaching project completion in 2024-2025, HNEI orchestrated a smooth transition to ensure long-term benefits. With the closure of U.S. Hybrid's local operations in 2024, the program adapted by assuming full in-house responsibility for station system controls and maintenance. Hydrogen trailers were safely decommissioned pending certification updates. NELHA management has expressed interest in operating the hydrogen station in support of a variety of projects including the development of a County of Hawai‘i MTA's West Hawai‘i bus maintenance facility, workforce development, and first responder training.

Overall, the project has achieved several key goals:

- *End-to-End Hydrogen System Deployment*: Designed, demonstrated, commissioned, and operated Hawai‘i's first public PEM-based refueling station, integrated with County bus operations;
- *Transit Fleet Integration*: Deployed and upgraded buses, documented real performance (efficiency, range, maintenance), and provided decision-quality data for County planning;

- *Technical Feasibility and Innovation*: Collected operational data at both station and bus levels, developed in-house control systems and manuals, and proved hydrogen transit viable under island conditions;
- *Workforce Development*: Trained dozens of drivers, mechanics, and first responders with sustained funding from FTA to ensure future pipeline capacity;
- *Public/Stakeholder Engagement*: Conducted tours, workshops, community events, and policy briefings, strengthening Hawaiʻi's role in global hydrogen collaboration;
- *Research/Science Contributions*: Advanced knowledge of corrosion challenges and materials performance, published peer-reviewed findings, and influenced design standards; and
- *Resilience and Continuity*: Demonstrated the viability of a bus-based export power for emergency use and transitioned infrastructure to NELHA as a lasting community and research asset.

Building on and supporting these efforts, between 2021 and 2025, portions of four awards funded by the Office of Naval Research (ONR): APRISES20 (N00014-21-1-2250), APRISES21 (N00014-22-1-2045), APRISES22 (N00014-23-1-2720), and APRISES23 (N000142412397) were used to support the operation and maintenance of the fueling infrastructure and collect data from the hydrogen fuel cell electric buses (FCEBs). These ONR funds were leveraged ongoing support from the State of Hawaiʻi and the County of Hawaiʻi.

Key contributions supported by APRISES23 funding included:

- Responded to the loss of U.S. Hybrid's Hawaiʻi technical support after corporate closure, which resulted in the temporary cessation of MTA fleet operations pending alternative maintenance solutions;
- Bus window replacement;
- Managed safe decommissioning and purging of hydrogen transport trailers, pending expensive hydrostatic certification required for mainland compliance due to local testing limitations;
- Began planning for a comprehensive shutdown and transfer of HNEI hydrogen station assets to NELHA management for future workforce development, first responder training, and infrastructure support;
- Completed a full overhaul of hydrogen dispenser control software, ensuring it is fully owned and maintainable by HNEI, accompanied by complete operational documentation and safety features;
- Conducted thorough station safety inspections, calibrations, and recertifications of fire, gas detection, and suppression systems, passing all UH Environmental Health and Safety audits;
- Replaced a critical electrolyzer primary control board (Figure 1.9), restoring full station functionality;

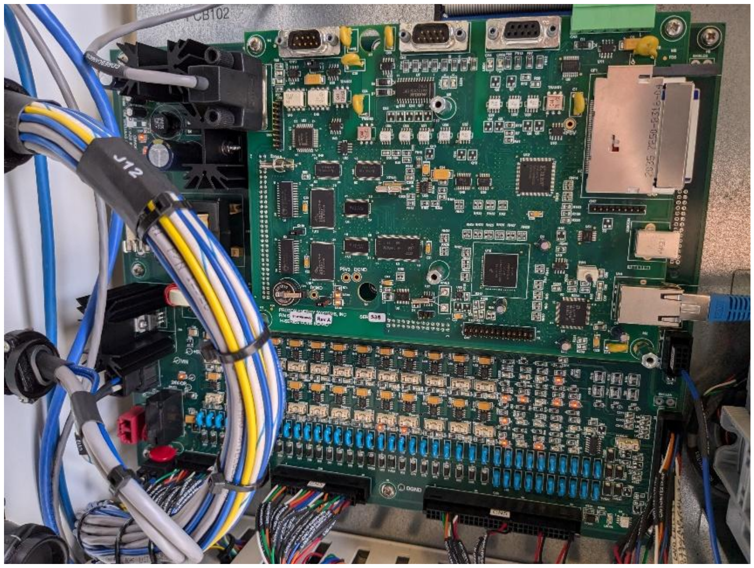

Figure 1.9. Replacement electrolyzer primary control board.

- Continued upgrades on the two 19-passenger buses with Hyundai 90 kW fuel cells and A123 lithium-ion batteries, funded by the County of Hawai‘i;
- Conducted targeted briefings and tours at NELHA for Japanese students from Shizuoka Prefecture, representatives from Honda North America and Honda Japan, and SunHydrogen—strengthening global and industry partnerships in hydrogen innovation and education;
- Implemented power monitoring systems (Figure 1.10), allowing power draw capping at 300 kW to minimize grid demand charges. This was integrated with NELHA's SCADA system that was developed by HNEI;

Figure 1.10. Power monitoring system with SCADA integration.

- Completed nitrogen purge of tube trailers for recertification;
- Completed all final reporting, documentation, and contract close-out activities as required by ONR termination directives; and

- Maintained community engagement and public outreach through presentations and tours despite program wind-down and helped the local community continue connecting with hydrogen transit benefits.

RESILIENT ENERGY SYSTEMS

Under APRISES23, HNEI continued development of enabling technology focused on the integration of new technology and reliable control at the grid edge. This research, conducted by HNEI's Grid System Technologies Advanced Research Team (Grid***START***) focused on extending the bidirectional EV charging demonstration project into the residential context through technoeconomic analysis of residential load, rooftop PV, stationary storage, and bidirectionally charged electric vehicles (EV) under time-of-use (TOU) pricing. Additionally, HNEI sought to continue efforts initiated under HNEI's Asia Pacific Regional Energy System Assessment (APRESA) program (ONR N00014-17-1-2923) by expanding reliability, stability, and resilience support activities to the broader Asia Pacific region. To achieve this, technical support including the application of modeling tools and capacity building was provided to organizations in the Cook Islands and Palau.

Bidirectional EV Charging Optimization

The electrification of transportation presents challenges for electric grids, such as increased electricity demand and altered load patterns. However, there is significant potential to utilize the flexibility of EVs for managed charging, offering benefits and services that can enhance economic value for EV owners while improving grid reliability and energy security. Toward that end, HNEI engaged in a collaboration with IKS Co., Ltd. ("IKS") on technology development, test, and demonstration of advanced control of two bidirectional EV chargers (Hybrid Power Conditioning System or H-PCS) on the campus of the University of Hawaiʻi at Mānoa (UHM). The H-PCS was developed by IKS with support from Hitachi Limited as part of the earlier JUMPSmart Maui smart grid demonstration project, in which HNEI was one of the partners.

The primary objective of this project was to minimize energy costs through optimized management of an EV fleet. To address the complex challenge of bidirectional EV charging in shared fleet applications, Grid***START*** developed and demonstrated advanced algorithms to manage the charging and discharging cycles of electric fleet vehicles. Figure 2.1 provides a summary of the project. In addition to the development of the advanced algorithms, the outcomes were intended to inform UHM's consideration of options such as fleet electrification, advanced car-sharing applications, and the integration of distributed alternative energy resources on campus.

Furthermore, the scalable field test results would enable the assessment of larger EV fleets in car-sharing systems such as might be found at DoD facilities, particularly for providing grid ancillary services.

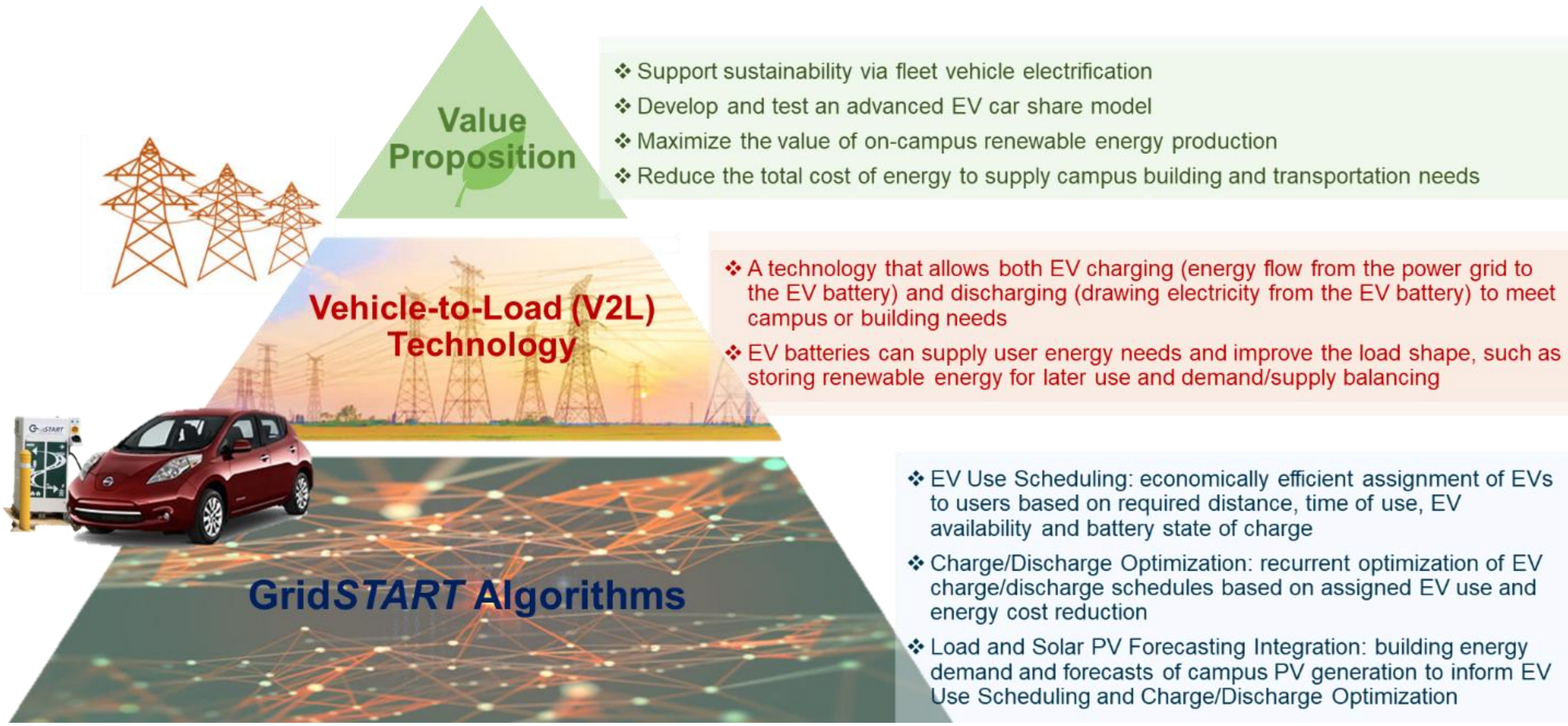

Figure 2.1. Overview of HNEI's bidirectional EV charging optimization project.

As previously reported, prior APRISES funding advanced the bidirectional EV charging optimization project through several major stages of development and demonstration:

- *Initial System Deployment*: HNEI coordinated extensively with IKS to procure and receive two H-PCS bidirectional chargers, overcoming significant international shipping delays caused by the COVID-19 pandemic. The hardware foundation of the demonstration site at UHM was designed and installed, including two H-PCS bidirectional chargers, transformers, a control box, and associated electrical infrastructure. Grid***START*** developed and integrated load forecasting tools using campus electrical data and machine learning algorithms. HNEI's solar forecasting system was incorporated to prioritize electricity generated from solar photovoltaic (PV) systems for EV charging. A web-based car scheduling application was designed and commissioned to coordinate shared vehicle use with optimized charging schedules. HNEI's patented Advanced Real-Time Grid Energy Monitor System (ARGEMS) was also implemented as the central controller for data collection, optimization, and execution of charge/discharge commands.
- *Algorithm Development and Field Commissioning*: The autonomous algorithms for cost-optimized bidirectional charging, integrating forecasting, scheduling, and EV battery telemetry were finalized. The operational system was fully commissioned, placing vehicles and chargers into daily use by authorized drivers. The team developed an autonomous lockbox key management system and introduced telematics-based EV monitoring for real-world driving data. Comparative analyses of unidirectional and bidirectional smart charging was conducted, which showed measurable cost savings and demonstrated higher benefits from bidirectional optimization. Results were disseminated through peer-reviewed publications and conference presentations, extending findings to international audiences. Grid***START*** explored EV integration into distribution grids, applying analysis tools to case studies in Vietnam for unidirectional charger deployment planning.
- *Advanced Modeling and Analysis*: Comprehensive economic analyses of campus building load profiles was conducted to evaluate the cost impacts of different EV charging strategies. HNEI developed a machine learning-based method (Bi-LSTM with least square optimization) for estimating EV energy consumption on pre-defined trips and validated with telemetric data. Applied training was also provided to undergraduate engineering students in optimization, programming, and grid-energy interface design.
- *System Optimization and Operational Assessment*: The EV charging management system was enhanced through continued monitoring and the refinement of algorithms to maximize vehicle utility and energy cost savings. Grid***START*** conducted detailed analysis of multiple Hawaiian Electric rate structures (Advanced Rate Design Schedules R, G, J, and Schedule P) to clarify their impacts on EV-enabled optimization scenarios. Real-world

charging and discharging patterns from the project fleet were investigated to inform refinements in models and fleet-scale optimization strategies.

- *Decision-Support Tools and Student Training*: A novel technoeconomic algorithm for optimal sizing of home stationary batteries and rooftop PV systems was developed in conjunction with EVs equipped with bidirectional charging capabilities. HNEI engaged graduate students in hands-on training to strengthen their skills in energy system operations, troubleshooting, and software development. Their work included the development of a user-friendly web tool that operationalizes the sizing algorithm for practical use. The team extended this work into a broader software-based design platform for optimizing household energy systems that integrate rooftop PV, stationary storage, and bidirectional EVs. A user-friendly interface for the platform was created to enable wider adoption, facilitate customer decision-making, and attract interest from industry partners.

Under APRISES23 funding, HNEI extended its economic analyses through the evaluation of a residential area with a total peak load of 400 kW and 50 kW of rooftop PV. The analysis assumed the participation of fifteen EVs, each with a 40-kWh battery capacity and a 6 kVA charger. The seven "cases" listed below were analyzed across three TOU rate scenarios (TOU_flat, TOU_low and TOU_high) to compare electricity costs:

1. Building load only (Base Case);
2. Building load plus 15 EVs with unidirectional charging (no intelligence);
3. Building load plus 15 EVs with smart unidirectional charging;
4. Building load plus 15 EVs with bidirectional charging;
5. Building load plus PVs and 15 EVs with unidirectional charging (no intelligence);
6. Building load plus PVs and 15 EVs with smart unidirectional charging; and
7. Building load plus PVs and 15 EVs with bidirectional charging.

The different TOU rates considered are illustrated in Figure 2.2. Comparative results for all scenarios are presented in Tables 2.1 and 2.2.

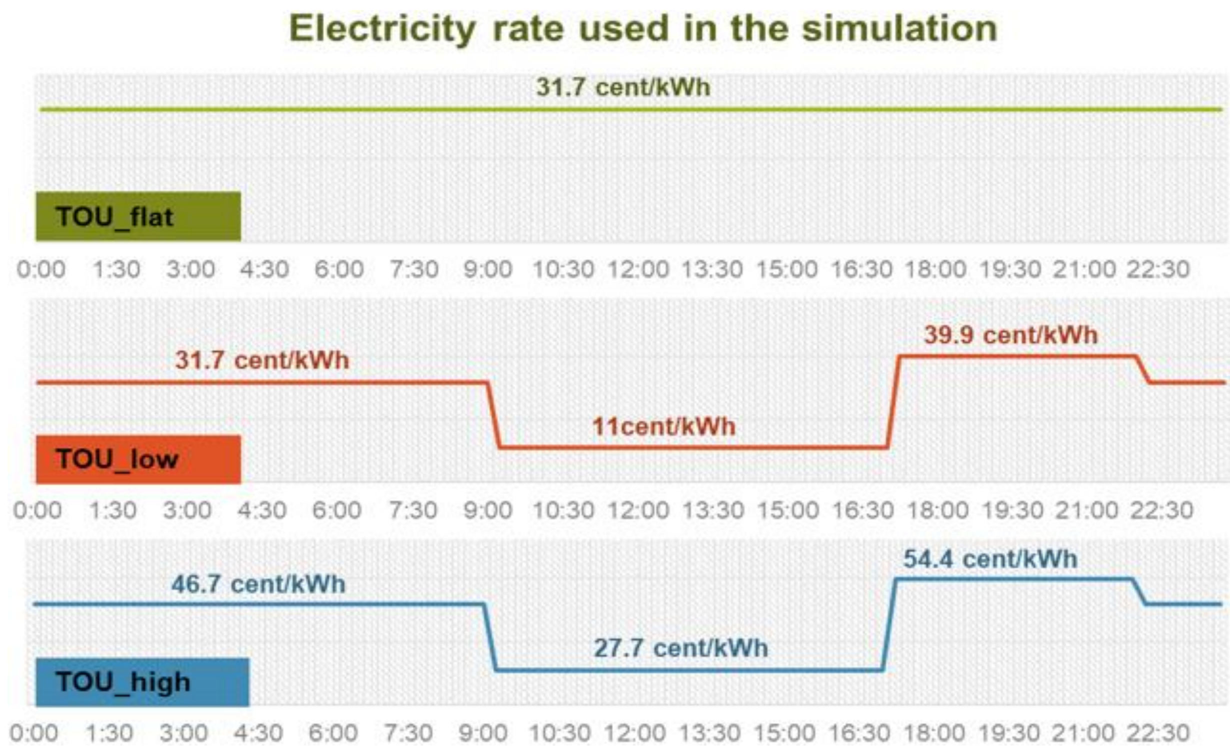

Figure 2.2. Simulated TOU rate structures.

Table 2.1. Comparison of simulated energy costs, in USD.

Case	Case Studies for Residential Load	TOU_flat	TOU_low	TOU_high
1	Load + gas cars usage (Base Case)	$29,970.86	$25,976.43	$39,940.82
2	Load + EV no optimization	$29,685.50	$25,179.54	$39,652.80
3	Load + EV unidirectional	$29,534.29	$25,080.72	$39,478.13
4	Load + EV bidirectional	$29,534.29	$21,884.53	$36,523.75
5	Load + PV + EV no optimization	$26,353.04	$23,671.54	$36,417.63
6	Load + PV + EV unidirectional	$26,201.83	$23,572.71	$36,242.96
7	Load + PV + EV bidirectional	$26,201.83	$20,376.53	$33,288.58

Table 2.2. Comparison of simulated energy costs, in percentage.

Case	Case Studies for Residential Load	TOU_flat	TOU_low	TOU_high
1	Load + gas cars usage (Base Case)	***Savings compared to Base Case (% per month)***		
2	Load + EV no optimization	0.95%	3.07%	0.72%
3	Load + EV unidirectional	1.46%	3.45%	1.16%
4	Load + EV bidirectional	1.46%	15.75%	8.56%
5	Load + PV + EV no optimization	12.07%	8.87%	8.82%
6	Load + PV + EV unidirectional	12.58%	9.25%	9.26%
7	Load + PV + EV bidirectional	12.58%	21.56%	16.66%

The analysis demonstrated that simply replacing gasoline-powered vehicles with EVs results in modest cost savings, especially under low TOU rates, where savings increase from 0.95% to 3.07% without any optimization applied. Implementing unidirectional EV charging yields a slight improvement in savings across all TOU structures. However, the adoption of bidirectional EV charging significantly enhances the economic benefits, particularly under high TOU rates, where monthly savings rise to 8.56%.

When rooftop PV systems are incorporated, overall savings increase dramatically. Even without optimization, the combination of PV and EVs achieves more than 12% savings under the TOU_flat rate. The greatest savings are realized when both bidirectional charging and PV are utilized, reaching 21.56% under TOU_low and 16.66% under TOU_high. This is primarily due to the system's ability to store excess solar energy and discharge it during periods of peak electricity pricing. These findings underscore the importance of intelligent charging strategies and responsive TOU pricing in maximizing the economic returns from integrated home energy systems.

Energy Regulatory and Technical Support for the Cook Islands

Utilizing ONR Asia Pacific Regional Energy System Assessment (APRESA) funding, HNEI's Grid***START*** developed strong relationships with several island nations and territories with island grids across the Asia Pacific region, including the Cook Islands. Project selection was guided by criteria such as projected demand growth, the potential to integrate variable and intermittent energy technologies, strategic importance to the United States, and the presence of a collaborative environment in which to conduct the work.

Over that past two years, HNEI effectively leveraged the APRESA funding to provide technical, regulatory, and policy support to Te Aponga Uira (TAU), the government-owned electric utility serving Rarotonga in the Cook Islands. In 2024 and 2025, through APRISES23 funding, the team built the first ever production cost model of the TAU grid, trained TAU personnel on and performed production cost modeling of the Rarotonga power grid. Concurrently, through APRESA, Grid***START*** developed and carried out a methodology for performing hosting capacity analysis of distribution feeders with higher standard service voltage (240 V single phase, 415 V three phase in the Cook Islands), applying it to the TAU's distribution feeders.

TAU, which serves approximately 5,000 customers, is responsible for about 90% of the Cook Islands' total electricity generation. The Rarotonga power grid has a peak demand of roughly 5.5 megawatts (MW). Approximately 85% of the energy comes from diesel generation, while the remaining 15% is generated primarily from solar photovoltaic (PV), with a small contribution from biomass. This includes a significant number of customer-owned distributed rooftop PV systems. Additionally, several utility-scale PV and battery energy storage system (BESS) projects on Rarotonga have been financed by international sources, such as the Te Mana o Te Ra project (Figure 2.3).

Figure 2.3. The Te Mana o Te Ra PV + BESS project (1 MW, 5.6 MWh) at the Rarotonga International Airport.

In September 2023, HNEI organized a one-day training workshop in Hawai‘i for the Board of Directors, Chief Executive Officer, and Chief Engineer of TAU. The workshop covered a range of topics, including Hawai‘i's energy transition, grid modernization, BESS, and a case study on distributed PV integration from Moloka‘i. During and after the workshop, HNEI and TAU engaged in discussions to identify areas for further technical and regulatory support.

In July 2024 at TAU's request, Grid***START*** conducted a week-long series of capacity-building presentations and meetings in Rarotonga. Participants included TAU management, the boards of directors of TAU and CIIC, and Prime Minister Mark Brown (Figure 2.4). The sessions addressed Hawai‘i's energy transition experiences, phased BESS implementation case studies for various Pacific Island Countries and Kaua‘i, and potential energy transition scenarios for Rarotonga, while also identifying further support needs for TAU. Following this visit, HNEI collaborated closely with TAU to collect data and information on the TAU power system and review their power flow model in PowerFactory, a proprietary power system analysis tool provided by DIgSILENT.

*Figure 2.4. Grid**START** staff with TAU leadership and Prime Minister Brown.*

Under APRISES23 funding, HNEI continued to support the Cook Islands' energy transition, building on the previous discussions and workshops held with TAU. Drawing from Hawai'i's experience integrating significant levels of variable and intermittent energy resources, Grid***START*** emphasized to TAU that successful energy transition requires robust grid planning based on holistic analysis of generation, transmission and distribution systems.

The team introduced the Scenario Analysis Interface for Energy Systems (SAInt), a proprietary software platform provided by Encoord Inc. SAInt enables integrated modeling of energy networks in a single platform, with the ability to conduct technoeconomic capacity expansion and energy production cost analysis combined with distribution/transmission system power flow modeling. In this context, HNEI organized a three-day workshop on SAInt in January 2025 and invited TAU members to participate. In close collaboration with Encoord, Grid***START*** initiated the process of transferring TAU's PowerFactory power flow model into the SAInt platform and began to build out TAU's generation resource portfolio within the production costing module of SAIntto facilitate a more comprehensive analysis of TAU's power grid.

HNEI subsequently initiated analytical studies to inform strategic planning and resource management for TAU. The team began to explore how different configurations and operational strategies, particularly those involving BESS resources, could impact overall grid performance and excess energy potential for added increments of intermittent energy resources. The analysis evaluated both existing operating practices and prospective strategies where BESS resources support system reserves. The results of these simulations revealed notable opportunities for operational improvements and cost savings if BESS assets are deployed for reserve management. The modeling demonstrated that the inclusion of BESS resource reduces the need to curtail PV output, thereby maximizing the energy contribution of the resources to the grid. Economic analysis further indicated that effective use of BESS for reserve provision could lead to substantial annual operational cost savings, with even greater benefits possible if multiple storage assets are coordinated for both reserves and energy shifting.

Energy Regulatory and Technical Support for Palau

Drawing upon ONR APRESA program funding, HNEI Grid***START*** established strong relationships with several island nations and territories across the Asia Pacific region, including Palau. As with our efforts in the Cook Islands, project selection was guided by criteria such as projected demand growth, the potential for integrating variable and intermittent energy technologies, strategic importance to United States interests, and the presence of a collaborative environment suitable for such work.

Over the past two years, HNEI has effectively leveraged the APRESA funding to deliver technical, regulatory, and policy support to the Republic of Palau's Energy and Water Administration (PEWA), the Republic's energy regulator, and Palau Public Utilities Corporation (PPUC), the government-owned electric utility serving the nation's main islands. Through APRESA, the team performed production cost modeling for Palau's national power grid.

The Republic of Palau has set an ambitious target to increase the share of electricity generated from alternative and sustainable energy resources from 20% to 100% by 2050. Securing financing for major alternative energy projects from international sources, such as the Asian Development Bank (ADB) and foreign direct investment, is critical to achieving these goals. For example, in 2023, Palau commissioned a 15.3 MW solar PV plus 12.9 MWh battery energy storage system (BESS) project, the largest of its kind in the Western Pacific region (Figure 2.5). Additional utility-scale BESS and substantial customer-sited rooftop PV rollouts are underway or being planned. This rapid increase in inverter-based resources (IBRs) on the PPUC grid has introduced significant technical, regulatory, and economic challenges in grid integration, operations, utility fiscal management, and the design of rooftop PV programs and tariffs.

Figure 2.5. PV Arrays at Palau's SPEC PV+BESS plant.

Before launching the distribution feeder PV hosting capacity study, HNEI focused on strengthening relationships with PEWA and PPUC through targeted capacity building and regulatory support. In September 2023, HNEI organized a comprehensive three-day training program in Honolulu for the Director of PEWA and PPUC staff. This training covered a range of topics, including Hawai'i's energy transition, alternative energy policies, ratemaking, competitive bidding, variable/intermittent energy integration, and interconnection requirements. These efforts were followed by ongoing engagement with Palauan stakeholders and a high-level technical and financial analysis of PPUC's grid operations, encompassing both existing and planned utility-scale and customer-sited PV generation, projected excess energy curtailment and fiscal implications, and BESS requirements.

Building on this foundation, a new grid code for Palau was developed and delivered in February 2024, which was subsequently adopted by PEWA. To facilitate effective implementation, a three-day in-person training was held in June 2024 at PPUC's offices in Koror, focusing on energy transition topics such as integrating variable/intermittent energy resources and practical aspects of grid code compliance (Figure 2.6). In October 2024, HNEI provided additional training in Koror on the newly adopted grid code, with an emphasis on streamlined and online application and review processes for distributed rooftop PV interconnections.

*Figure 2.6. Grid**START**-led transition capacity building at PPUC.*

In 2024 and 2025, through APRISES23 program funding, Grid***START*** conducted a detailed survey of a selected site for a solar photovoltaic (PV) hosting capacity study and began the development of a corresponding system model. Drawing on its prior experience conducting PV hosting capacity studies for Maui and other projects, Grid***START*** has developed and refined a stochastic analysis-based methodology to evaluate PV hosting capacity on distribution feeders. This methodology is designed to support the reliable and secure operation of distribution systems with high levels of PV penetration. Leveraging this expertise, we identified the need for a PV hosting capacity analysis in Palau, given the nation's increasing adoption of both rooftop and utility-scale solar PV, as well as its ambitious alternative energy targets. Such an assessment was recognized as highly relevant and beneficial for Palau's energy planning efforts.

HNEI's Grid***START*** initiated a PV hosting capacity study for Palau's distribution network. After reviewing available data and feeder characteristics, the "Airport Feeder" was selected as the study site due to PPUC's access to annual hourly feeder load data for this circuit. While the Airport Feeder already included some rooftop PV installations, initial assessments indicated that there was potential to accommodate additional distributed PV.

To support this analysis and address the growing complexity of Palau's grid, Grid***START*** utilized PowerFactory, a commercial grid modeling software developed by DIgSILENT, to model the feeder power flow. PowerFactory is a widely-used power system analysis tool that supports power flow modeling and simulation of generation, transmission and distribution networks. Its features allow for the representation of various feeder configurations, including multi-phase and single-wire earth return systems, which are relevant to Palau's distribution network. By applying PowerFactory, the team would be able to analyze feeder performance, assess operational constraints, and evaluate the impacts of increased distributed generation. However, the PowerFactory software suite alone is unable to conduct the stochastic analysis-based methodology Grid***START*** has developed to evaluate PV hosting capacity on distribution feeders, and thus specialized in-house developed code that interacts directly with the PowerFactory software is applied. This state-of-the art modeling work provides a technical foundation for planning and decision-making as Palau moves toward higher levels of variable/intermittent energy integration.

Since PPUC did not have an existing feeder model, HNEI, with support from PPUC personnel, conducted a detailed field survey in late October 2024. This effort involved mapping transformers, customer locations, wire sizes and typical rooftop PV system sizes within the Airport Feeder's service area. Using the collected field data, we began constructing a detailed power flow model of the Airport Feeder within the PowerFactory platform. Figure 2.7 shows Grid***START*** and PPUC staff field surveying transformers during this process.

Figure 2.7. HNEI and PPUC staff conducting a field survey of transformers.