FINAL TECHNICAL REPORT

Executive Summary

Asia Pacific Research Initiative for Sustainable Energy Systems 2019

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

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EXECUTIVE SUMMARY

This report summarizes work conducted under Grant Award Number N00014-20-1-2270, the Asia Pacific Research Initiative for Sustainable Energy Systems 2019 (APRISES19), 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 APRISES19 comprises research, development, testing, and evaluation (RDT&E) over a range of technical areas. These include Electrochemical Technologies with a focus on fuel cells and batteries; Alternative Fuels including carbonization of biomass, marine fuels, and hydrogen; Resilient Grid Systems including development and demonstration of novel technologies for advanced smart microgrids and resource adequacy studies for the Hawaiʻi electrical grids; and work on Advanced Materials for energy applications including a novel forward osmosis water purification system and printable polymer composites for photovoltaic and other electronic applications. Makai Ocean Engineering, under subcontract to the University of Hawaiʻi, also continued their efforts to develop high-performance, low-cost heat exchangers. A brief summary of results by major task follows.

Task 1, Program Management and Outreach, supported senior faculty and project support personnel responsible for overall program management and coordination, development and monitoring of partner and subcontract agreements, and preparation of reports and outreach materials for ONR and other stakeholders.

Task 2, Electrochemical Technologies, included RDT&E in the areas of fuel cells and Li-on batteries. Progress in each of these areas is summarized below.

Under Subtask 2.1, Fuel Cell Testing and Development, HNEI's research encompassed five projects in three areas: 1) the development of a contaminant-tolerant fuel cell leveraging high temperature proton exchange (HTPEM) technology, with a focus on power systems for unmanned aerial vehicles (UAV); 2) advancements in materials to enable both in-situ and ex-situ strategies for contaminant mitigation and performance enhancement; and 3) the refinement of advanced diagnostic tools for fuel cells, supporting the R&D initiatives of both HNEI and the Naval Research Laboratory.

2.1a) Contaminant Tolerant Fuel Cell Development: Despite HTPEM's inherent contaminant tolerance due to its operating temperature range, limitations exist. HNEI conducted a review on fuel and air contaminants in HTPEM, focusing on identifying critical contaminants and their mechanisms as part of the contaminant-tolerant fuel cell program. The review highlighted that nitrogen species (e.g., NO, NO_x, NH_3) must be avoided as they irreversibly block catalysts and hinder proton conduction, with alternative catalysts providing limited mitigation. Conversely, sulfur species (e.g., SO_2, H_2S) showed a negligible impact on HTPEM, with performance losses being recoverable. VOCs like benzene, a common battlefield contaminant, are unlikely to pose issues but require evaluation. Future efforts should focus on nitrogen-based compounds through system-level strategies (e.g., filtration media) or fuel cell-level innovations like new proton conductors or selective oxidation layers to counteract their effects.

2.1b) Proton Conductive Electrolytes for HT-PEMFC: The focus of this activity was to develop an inorganic electrolyte with high proton conductivity for use as the cathode catalyst layer able to operate under high temperature and low humidity. Under this award, a novel inorganic proton conductive electrolyte with multilayer structures was designed and successfully synthesized, and the production was scaled up to ~10g in one batch. The particle size and proton conductivity of the powders, the thermal and electrochemical stability, and the solubility of the material were characterized. The results indicate that the down selected material is a promising candidate to be used in the cathode catalyst layer of HT-PEMFCs operating at 150-200°C at low or without humidification. Under future funding, the properties and performance of the materials will be further studied and improved with the optimization of the synthesis procedures. The particle size will be optimized to make the powder suitable for the catalyst layer. The selected materials will be integrated into the cathode catalyst layers of HT-MEAs, and the performance will be evaluated at 150-200°C.

2.1c) Application of Electrochemical Impedance Spectroscopy for Analysis of Fuel Cells: HNEI continued the development and refinement of advanced diagnostic methods, such as electrochemical impedance spectroscopy, for analyzing fuel cell operation. The application of a physics-based 1d+1d model, which incorporates liquid water transport in the cathode catalyst layer (CCL), revealed that water saturation in the CCL remains nearly independent of cell current density. This is due to the increasing liquid pressure gradient that facilitates liquid water removal from the CCL. Simultaneously, oxygen diffusivity in the gas phase of the catalyst layer increases with rising cell current density. This behavior is attributed to the fact that, at low current densities, electrochemical reactions predominantly occur in narrow pores, where Knudsen oxygen diffusivity is relatively low. As the current density increases, larger and better-connected pores with higher oxygen diffusivity become more dominant in current conversion, leading to an overall increase in effective oxygen diffusivity. The insights gained into water distribution and oxygen diffusivity as a function of current density are important for developing guidelines for the rational design of electrode texture and morphology to optimize fuel cell performance.

2.1d) Transition Metal Carbide Catalysts: Efforts under this activity focused on the development of transition metal carbide catalysts for electrochemical applications, including fuel cells, water electrolyzers, and vanadium redox flow batteries. Vanadium carbides and titanium vanadium composite oxides nanoflakes were synthesized and exhibited excellent thermal stability, oxidation resistance, acid resistance, and electrochemical stability. Vanadium carbide nanoflakes were initially evaluated by ex-situ cyclic voltammetry experiments as catalysts for V^{3+}/V^{2+} redox reactions. The results indicated that vanadium carbide nanoflakes showed good catalytic activity and reversibility toward the V^{3+}/V^{2+} redox reaction. Further studies will be conducted to reveal the electrochemical characteristics of carbides as catalysts for hydrogen evolution reaction.

2.1e) In-situ Catalytic Conversion Layer Mitigating Contamination in Proton Exchange Membrane Fuel Cells: Air contaminants can significantly decrease the performance and durability of PEMFCs even with trace concentrations. Few methods have been proposed for the recovering of contaminated PEMFCs, namely, electrode potential scanning, polarization curves. Contaminant-tolerant catalyst development and an air intake filter design are other important mitigation methods. However, all of them present undesired side effects such as undesirable cell shut down, performance degradation, and some of the contaminants through over time. Under this activity, HNEI continued work to develop an in-situ catalytic conversion layer to mitigate contamination in PEMFCs. Contaminant-active catalysts based on transition metal carbides and composite oxides were synthesized and investigated. Carbides and composite oxides exhibited catalytic activities toward the electrochemical oxidation of aqueous SO_2 generated in situ. Future studies will include integration of contaminant-active catalysts in the membrane electrode assembly, regulation the composition and structure of in-situ catalytic conversion layer to maximize catalyst utilization and minimize transport resistance, and evaluation and optimization the contaminant tolerance of PEMFCs.

Under subtask 2.2, Battery Characterization and Modeling, HNEI research covered two main areas: 1) the expansion of HNEI's mechanistic diagnosis and prognosis battery modeling framework to additional degradation modes and 2) laboratory characterization that supports field deployment of battery energy storage systems.

HNEI developed new approaches to improve the simulations of blended electrodes that are becoming more common in commercial cells and that might not be compatible with typical diagnosis tools. The three major types of blends, the mix of active materials, electrode inhomogeneities, and lithium plating, were successfully emulated by combining new paralleling strategies, the implementation of the impact different inhomogeneity modes, and an additional lithium plating resistance taking into consideration the rate dependence of the plating potential.

In support of field deployment, HNEI initially focused on the characterization of relaxation curves, the only common element in most of deployed battery usage, with the investigation of the second derivative of the relaxation curve vs. different depth of discharge, regimes, and temperatures. The method was shown to have significant limitations preventing its application in deployed systems. HNEI them explored a Li-ion degradation mode analysis which was shown to be valid on one of the first commercially available Sodium-ion batteries which should allow fast development of diagnosis and prognosis technologies. Other Na-ion battery chemistries are under investigation.

Under **Task 3**, HNEI continued research in three areas: constant volume carbonization of biomass, fit-for-purpose characterization of marine fuels, and hydrogen refueling technology.

Under Subtask 3.1, Constant Volume Carbonization, HNEI continued experiments and testing to evaluate the effects of independent variables including reactor temperature, reaction time, biomass feedstock, biomass moisture content, and acetic acid content on transient plastic phase (TPP) formation, fixed carbon yields, and ultimate tensile strengths of biochars. Temperature had the greatest effect on fixed carbon yields and ultimate tensile strengths while reaction conditions that led to improved ultimate tensile strength sacrificed fixed carbon yield. Details of the work were published in *Energy and Fuels.*

Conventional fossil fuels have a complex composition, including a diverse mix of hydrocarbons, accounting for approximately 98-99% of the fuel. In addition, certain fit-for-purpose properties, such as lubricity, electrical conductivity, storage stability, and thermal stability, are significantly influenced by trace fuel species, primarily heteroatomic organic species (HOS). Under Subtask 3.2, in collaboration with personnel from the U.S. Navy Fuels Cross-Functional Team at Naval Air Station Patuxent River (NAVAIR), HNEI continued efforts to identify and characterize trace quantities of HOS in aviation, maritime, and diesel fuels. A primary objective of this task was to assess the repeatability of two-dimensional gas chromatography (GC×GC) analysis of nitrogen containing compounds (NCC) using a nitrogen chemiluminescence detector (NCD). The NAVAIR team selected seven marine gasoil (MGO) samples for round-robin testing with UHM and the research group at the Navy Technology Center for Safety and Survivability, Naval Research Laboratory (NRL). The results of this comparison are summarized in Task 3.2 of the report.

The primary effort under Subtask 3.3 was to support the development of refueling infrastructure for heavy duty hydrogen vehicles and assessment of the performance of fuel cell-electric hybrid buses (FCEBs) using the NELHA test site, built and managed by HNEI. Under APRISES19 funding, HNEI supported the development of procedures to manage the cost of hydrogen production; data collection from Bus #111, the first to become operational; and planning with the Hawaiʻi Mass Transit Authority (MTA) for deployment of remote dispensing at the MTA Hilo bus maintenance facility. While the station remains fully operational, corporate changes with the vendor providing bus support are impacting operations with an uncertain future.

Under **Task 4**, Resilient Energy Systems, HNEI continued research to enable the development of resilient, reliable, and secure energy systems operating with a high penetration of variable renewable generation technologies. The proposed work included two closely integrated activities. Under Subtask 4.1, HNEI continued development of enabling technology focused on the integration of new technology and reliable control at the grid edge. Subtask 4.2 focused on power systems analysis to ensure that the energy systems and related critical infrastructure on Oʻahu and the other Hawaiian Islands, home to the Pacific Command and the largest military bases in the Asia Pacific region, meets the reliability, security, and resiliency needs of DOD as additional variable generation technologies are integrated into the grid. This latter activity leveraged resources from the Energy Systems Development Special Fund (ESDSF) managed by HNEI (also known as "barrel tax").

Under Subtask 4.1, Resilient Grid Systems, research was conducted to support the development and deployment of reliable and resilient energy systems to bolster energy security, reliability, and resilience in Hawaiʻi and Department of Defense facilities in Japan. This effort, primarily executed by HNEI's Grid*START* (Grid System Technologies Advanced Research Team), built upon prior research aimed at enhancing grid performance reliability amidst high penetrations of renewable energy, undertaking a range of research and development activities. Specific subtasks included: a) electric vehicle (EV) charging infrastructure Master Plan development for the United States Marine Corps (USMC) Camp Fuji, Japan; b) DC microgrid system enhancement on Coconut Island and an electric boat; c) advanced EV charging management system expansion with economic analysis tools and Machine-Learning (ML) based optimization; d) hardware and software updates for the advanced conservation voltage reduction (CVR) system maintenance; e) development of an analytical tool for customer Virtual Power Plant (VPP) program participation decisions; and f) development of a dual-stage algorithm for photovoltaic (PV) hosting capacity assessment with improved performance. A key emphasis throughout these activities was on grid-edge technologies, distributed energy resources (DER), and microgrid applications.

4.1a) EV Charging Infrastructure Master Plan for USMC Camp Fuji, Japan: HNEI assisted USMC Camp Fuji in creating an EV infrastructure Master Plan to strategically transition its non-tactical vehicle fleet to zero-emission vehicles, as mandated by Presidential Executive Order 14057. The plan involved a detailed assessment of existing non-tactical vehicles and electrical infrastructure at Camp Fuji. It provided plans for charging infrastructure locations and recommended upgrades to the Camp's infrastructure. The finalized Master Plan was presented and well-received by Camp Fuji personnel in early 2024, bringing the project to conclusion.

4.1b) Coconut Island DC Microgrid Project: This project initiated under previous APRISES funding was continued with the objective of demonstrating the performance and resilience of a DC microgrid designed to serve critical loads within two buildings on Coconut Island, delivering reliable power to critical loads during interruptions of grid supplied power, and providing the island with clean electrified transportation options powered primarily by the sun. Under this award, HNEI completed several key system changes and upgrades, including the installation and commissioning of a new OPTO 22 Edge industrial controller, enhancement of the DC microgrid controller software, and the development of a real-time monitoring dashboard. Additionally, the swappable batteries and charging system were decommissioned, and the E-boat's batteries and PV system were upgraded to a fixed placement 18.2 kWh battery and a consolidated PV system, enabling prospective vehicle-to-grid (V2G) functionality.

4.1c) Bidirectional EV Charging Optimization: HNEI continued to collaborate with IKS Co., Ltd. (IKS) on technology development, testing, and demonstration of advanced control of two bidirectional EV chargers at the University of Hawaiʻi at Mānoa (UHM). To tackle the complex optimization problem and demonstrate the use of bidirectional EV chargers, the team is developing, evaluating, and demonstrating the performance of novel algorithms to optimize the charge/discharge of shared fleet vehicles for energy cost minimization. Under this award, the project developed an EV charging management system and conducted economic analyses showing bidirectional charging to be the most cost-effective across campus buildings. A key achievement was the creation of a techno-economic tool for homeowners to optimize their PV and battery systems alongside bidirectional EVs, demonstrating the economic benefits and potential to reduce home battery size. Additionally, a ML-based model for estimating EV energy consumption was developed. The project also resulted in a peer-reviewed publication and provided training for engineering students. Future work includes further improving the charging management system and exploring other optimization objectives.

4.1d) Advanced Conservation Voltage Reduction Demonstration: HNEI continued efforts on the demonstration of advanced CVR at USMC Camp Butler in Okinawa, aiming to improve energy efficiency on a distribution circuit serving the Plaza Housing complex. The team implemented advanced CVR by using a new voltage regulator (VR) to manage voltage for seven service transformers. Under previous APRISES awards, infrastructure was developed, including the VR and an advanced CVR device, consisting of a reactive power resource and a Volt-Var controller. APRISES19 activities included separating the communication system, assessing damage from Typhoon Khanun, which temporarily interrupted operation but did not damage the VR, and upgrading the advanced CVR device. Data collected showed a CVR factor of 0.75% to 0.93% and a 2.25% voltage reduction, with potential monthly energy savings. Further testing of the advanced CVR device is planned.

4.1e) Hawaiʻi BESS + PV Virtual Power Plant Demonstration: Leveraging four (4) distributed battery energy storage systems (BESS) and solar PV systems (BESS + PV) acquired from a completed smart grid project funded by the New and Industrial Technology Development Organization (NEDO) of Japan, HNEI Grid*START* conducted research and development on VPP to analyze functional and economic trade-offs in VPP dispatch. Under previous APRISES funding, the BESS + PV units were connected to the local utility's power system, and a local energy management system with a web-based interface was developed to externally optimize and control the units. Under this award, the team developed a methodology to compare VPP participants with non-participants. A key finding was that committing an optimized battery capacity to the VPP program yielded lower electricity costs for customers than committing the maximum capacity called for by the program. The project also involved creating a real-time monitoring dashboard and provided training for a graduate student. The knowledge gained from this demonstration will be used for capacity building in the Asia-Pacific region. With the project objectives now complete, the system decommissioning has commenced.

4.1f) Automated Distribution Circuit PV Hosting Capacity Estimation: HNEI's research focused on automating the estimation of PV hosting capacity in distribution circuits to accommodate more solar power while maintaining grid reliability. HNEI significantly advanced PV hosting capacity estimation methods developed under previous DOE and APRISES funding. Building on earlier DOE project work in MATLAB, APRISES19 efforts utilized OpenDSS Direct in Python to develop higher efficiency estimation methods. This included an original algorithm and a more advanced two-phase algorithm that considered multiple grid constraints such as voltage limits, thermal overloads, and power losses. Both methods were tested on the IEEE 13-Bus system. The analysis of the original method showed the system's overall hosting capacity ranged from 112% to 285% depending on the constraint. The two-phase method initially estimated hosting capacity at 162%, refined to 124%, and demonstrated improved stability and significantly faster computation times compared to the original method. This advanced method is considered more valuable for practical applications, and its learnings will be applied to support grid operators in the Asia-Pacific region.

Subtask 4.2, studied the resiliency of Hawai‘i's grids. In recent years, Hawai‘i has experienced rapid growth in solar energy driven by high oil prices, favorable policies, and aggressive goals to achieve 100% renewable electricity and carbon neutrality by 2045. Most recently, this growth has been in the form of large-scale utility solar systems combined with battery energy storage which are being deployed at a scale not yet seen in other parts of the United States or globally. Simultaneously, the conventional coal and oil generation plants, such as the AES coal plant, are being retired from operation. Various stakeholders have expressed concerns about grid reliability with large scale deployment of these variable generation solar systems. Over the past several years, funded in part from the APRISES awards with significant supporting funding from the State of Hawai‘i Energy Systems Development Special Fund, HNEI has conducted resource adequacy studies for the Hawai‘i electrical grids, calculating the amount of solar and storage capacity that would be needed to ensure resource adequacy (reliability) at various levels of coal and oil retirements. HNEI analysis indicates that up to 70% of O‘ahu's electricity could be derived from variable renewable sources (e.g. solar) without significant curtailment of the solar energy and without any loss in reliability as long as adequate amounts of fast-response generation is available during extended periods of low renewable resource. Results of the HNEI analysis are being reported to various stakeholders including the utility, the legislature and the Hawai‘i Public Utilities Commission.

Task 5, Advanced Materials, comprises two subtasks that includes the development and testing of using forward osmosis technology for energy efficient water purification and the development of polymer composites for use in a variety of applications where conformable, corrosion-resistant, and tunable optoelectronic property materials are necessary.

Under Subtask 5.1, the HNEI-fabricated FO system was optimized and in-depth draw solutions testing was initiated using commercial (including glucose and ammonium chloride) and new draw solutes (including potassium lactate and metal containing ionic liquids), which are summarized further below. The performance of the draw solutes was evaluated in terms of water flux and the total mass of water transported through the CTA membrane over a 24-hour period. The performance of the 1 molar draw solutions was tested against a feed solution of deionized water and Hawai‘i's Ala Moana seawater. The potassium lactate performed the best among the draw solutes studied with deionized water and seawater feed solutions, warranting further studies in the future. The potassium lactate is an approved food additive safe for human consumption suggesting its high suitability as a draw solute for drinking water applications.

Under Subtask 5.2, the research team at HNEI's Thin Films Laboratory developed a new type of polymer composites integrating multi-functionalities relevant to the U.S. Navy, including resistance against corrosion, lightweight and flexible, tunable dielectric-optical-electrical characteristics, as well as conformability to complex shapes. This technology consists of particles with specific material properties (e.g., semiconducting or metallic) protruding out of a transparent non-conductive polymer matrix. To create these transparent conductive composites (TCCs), particles are first dispersed into a liquid epoxy. The particle/epoxy dispersion is then formed, pressed, and cured. The forming process can be easily modified to either permanently bond TCCs onto parts or completely liberate it and create freestanding layers. Unlike other conductive flexible polymers, where conductive media are coated on top the substrate providing only *in-plan* conductivity, TCCs innovate by allowing the particles to protrude out from the hardened epoxy matrix, providing *out-of-plan* conductivity. Our team has thus far been successful in fabricating layers using 50-micron metallic particles embedded in hardened epoxy with both optical transmittance (>90% in the UV(250nm)-IR(2500nm) region) and out-of-plane conductivity (<0.2 ohm.cm) out-performing those of commercial transparent conductive ($F:SnO_2$; FTO) substrates. TCCs have great potentials in many applications where materials with good conformability to shapes, resistance against corrosion, and tunable optoelectronic properties are necessary. In in-mold electronic applications, TCCs can be used to isolate on-board electronic circuits or devices from atmospheric effects while allowing electrical access to interconnects. In electrochemical power systems (batteries, fuel cells) and organic/hybrid solar cells, TCCs can be applied as barriers against degradation. The nature of the particles can also be modified to be selective to specific electrochemical reactions (e.g., PGM or PGM-free catalysts for hydrogen evolution reactions). Finally, TCCs can be used to isolate metallic parts on shift and aircrafts from corrosive environments while preventing electrostatic buildup. This work is continuing.

Task 6, Advanced Heat Exchanger Development, continued to support the development of high-performance thin foil heat exchangers for use in seawater-refrigerant, air-water, and water-water applications. The work supported under this award was conducted between June 2023 and January 2024. In this period, Makai's efforts included improving TFHX fabrication methods, continued characterization of TFHX thermal and structural/mechanical performance, and investigation of biofouling mitigation methods. During this period, Makai finalized the pass-through seawater air conditioning (TFAC) design and developed a cassette-style design for large-scale applications which is expected to reduce the total unit cost by eliminating individual modules and improve performance by eliminating two 90° turns in the seawater path. Makai also improved fabrication speed, implemented the post-expansion repair method, and improved the quality of the cut-edge. Plate fabrication time was improved from 16.7 min to 12.4 min with an overall success rate of 68%. Makai also tested three ammonia-seawater (OTEC) four- port TFHXs. Performance data was fed into the OTEC Power Calculator to evaluate the different TFHX designs in the context of an OTEC power plant. The OTEC Power Calculator accounts for parasitic losses related to the total amount of seawater flow through the system, not just through the heat exchangers.

This final report describes the work that has been accomplished under each of these tasks, along with summaries of task efforts that are detailed in journal and other publications, including reports, conference proceedings, presentations, and patent applications. **Publications produced through these efforts are linked below and available on HNEI's website at https://www.hnei.hawaii.edu/publications/project-reports/aprises-19/.**