FINAL TECHNICAL REPORT

Executive Summary

Asia Pacific Research Initiative for Sustainable Energy Systems

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March 4, 2019 through November 27, 2023

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This report summarizes work conducted under Grant Award Number N00014-19-1-2159, the Asia Pacific Research Initiative for Sustainable Energy Systems 2018 (APRISES18), funded by the Office of Naval Research (ONR) to the Hawai‘i Natural Energy Institute (HNEI) of the University of Hawai‘i at Mānoa (UH). The work conducted under APRISES18 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 novel biocarbons from bioresources, marine fuels, and hydrogen; Resilient Energy Systems including development of novel technologies for advanced smart microgrids, reliability, and resilience for the O‘ahu grid, and a study to characterize air quality in a mechanically ventilated room; and work on advanced materials for energy applications including a novel forward osmosis water purification system and printable photovoltaics. Makai Ocean Engineering, under subcontract to the University of Hawai‘i, also continued their ongoing efforts to develop high-performance, low-cost heat exchangers. A brief summary of results by major task follows.

Task 1, Outreach and Program Management, 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 mainly in the area of fuel cells. Substantial progress was made in each of these activities.

HNEI continued to support NRL’s attritable fuel cell program and initiated the supporting laboratory work to implement high temperature solutions. HNEI provided consulting and computational modeling support to NRL’s program which focused on developing new fuel cell architectures aimed targeting the Navy’s growing interest in the development of attritable, lower cost technologies. HNEI also developed a 5 cm^2 flow-field plate for use in the existing 50 cm^2 hardware to support the testing and development of high temperature proton exchange (HTPEM) membrane electrode assembly (MEA). Initial evaluations of the hardware were performed using a commercially available Advent Technologies Polybenzimidazole (PBI) HTPEM MEA. Initial diagnostics of the new test rig were completed. The data produced in these studies will also be

used as a baseline comparison for benchmarking HNEI's in-house MEA development and development under the attritable fuel cell program.

In a continuation of our efforts to understand the operation of fuel cells under harsh environment, HNEI evaluated effects of NO_2 concentration in air stream on performance of high- and low-Pt loaded PEMFCs and their recovery. The difficulty recovering cell performance after exposure to NO_2 and the greater impact on low-Pt PEMFCs supports the conclusion NO_2 should be removed from the air stream prior to flow into the fuel cell.

Under APRISES18 funding, HNEI also continued to explore analytic techniques for analysis and improvement of fuel cell performance. A previously developed limiting-current methodology to assess mass transport limitations was used to compare performance of two different flow-field geometries providing important insights into the management of the mass transport resistances. In a related task, HNEI continued its development of a computationally fast approach for to analyze impedance spectra based on distribution of relaxation times (DRT). Several publications based on this work have been published.

Building on previous work that showed the improved contaminant tolerance of anion exchange membrane fuel cells (AEMFCs), research also continued in this area. This work continued efforts to develop contaminant tolerant AEMFC technology. In a new approach to solve water management problems, HNEI explored the development of new catalysts with optimal porosity, hydroxide ion conductivity and thickness to insure development of three phase boundaries, and sufficient reagents transport as well as adequate choice of gas diffusion layers (GDLs) for better water management. Work also progressed on the development of harmonized testing protocols and procedures for AEMFC.

Under APRISES18, HNEI also conducted exploratory research in three areas: development of transition metal-carbide catalysis, vanadium flow batteries using high concentration electrolytes, and solar thermal desalination using ion exchange membranes. Building on past work, a bimetallic TiVC catalyst with low percentage of Ti was shown to increase stability without affecting the catalytic activities. Work in this area is continuing. The research in the other two areas showed promise and proposals have been submitted to other agencies, but work under the APRISES awards will be discontinued.

Task 3, Alternative Fuels, continued research supporting three subtasks.

Under Subtask 3.1, HNEI continued experiments and testing to evaluate pressurized carbonization as a tool to treat and stabilize materials representative of waste streams from contingency bases. In past work, reaction conditions leading to the production of a transient plastic phase solid were identified. Under this award, experiments with a variety of feedstocks demonstrated that plasticized biochar can be produced from a variety of different feedstocks. The results also showed increasing the water content of the feedstock while also reducing the reaction time improves the mechanical properties of the biocarbon formed from the plasticized biochar intermediate.

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. Comparison of HNEI and NAVAIR characterizations provide a baseline measurement. The goal of future work will be to create an accepted, standard GC × GC method for analyzing other HOS (e.g. sulfur containing compounds and additives) in fuels.

The primary effort under Subtask 3.3 was to support 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 APRISES18 funding, HNEI supported the commissioning of the hydrogen station which is now fully operational; the commissioning of the first MTA fuel cell electric bus which was put into service in March 2023; coordination with the County R&D department and MTA to develop deployment concepts for three buses as well as initiation of negotiations for the county to assume a large portion of operation costs; and the development of plans for installation of remote dispensing equipment at the MTA Hilo bus maintenance facility. With the system now fully operational, the focus of future work will include commissioning of the two other buses for public transit and detailed analysis of the technical and economic performance data on bus and hydrogen station operations.

Task 4, Resilient Energy Systems, comprises three distinct subtasks: development of resilient grid systems, testing and modeling of battery systems, and a smaller task on air quality and energy efficiency in the built environment.

Under Subtask 4.1 Resilient Grid Systems, research was conducted to develop and assess the performance of innovative technologies and methodologies aimed to improve or ensure the operability and resiliency of the electricity grid during natural disasters and intentional acts of disruption, as well as renewable energy generation and active management and control of the energy systems. Specific subtasks included: a) an energy assessment of the Marine Corps Base Hawaiʻi; b) installation and commissioning of a DC microgrid system on Coconut Island; c) evaluation of the algorithms and web system for a bidirectional EV charging demonstration; d) improvement and maintenance of an advanced conservation voltage reduction system due to environmental challenges; e) development of a health assessment system for distribution transformers; and f) advancement of PV hosting capacity estimation method applications. This work was conducted primarily by HNEI's Grid***START*** (Grid System Technologies Advanced

Research Team). Under a request from the Naval Facilities Engineering and Expeditionary Warfare Center, HNEI also utilized APRISES18 funding for a study to develop an understanding of the existing infrastructure of the Red Hill Tanks.

4.1a) Under previous APRISES and this APRISES18 funding, HNEI assisted MCBH in developing their IESP, delivering a preliminary draft covering Stages 1-4 by October 2020. This draft included an initial analysis of MCBH's existing electrical infrastructure and load demands. The Marine Corps Installations Command (MCICOM) ultimately took over efforts to complete IESPs for all installations under its jurisdiction. However, MCBH sought HNEI's continued expertise to address base energy security gaps and explore alternative energy resilience solutions. This resulted in the EG&R Assessment, focusing on Stage 5's objective: identifying solutions for MCBH's 14-day energy resiliency requirement. The assessment evaluated various microgrid designs, including a base-wide solution, and smaller microgrid scenarios at the substation and feeder levels that maintain power to priority loads on the base.

4.1b) The Coconut Island DC Microgrid Project was initiated under previous APRISES funding with the objective of demonstrating the performance and resilience of a DC microgrid designed to serve critical loads within two buildings on Coconut Island, including 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 APRISES18 funding, HNEI completed wiring for the entire system, an electric power flow metering system was procured and installed, installed and tested a new DC to AC inverter, commissioned inverters and charge controllers, and contracted the microgrid controller installation.

4.1c) HNEI is collaborating with IKS Co., Ltd. (IKS) on technology development, testing, and demonstration of advanced control of two bidirectional EV chargers (H-PCS) on the campus of the University of Hawaiʻi at Mānoa (UH). To tackle the complex optimization problem and demonstrate the use of bidirectional EV chargers, HNEI Grid***START*** is developing, evaluating, and demonstrating the performance of novel algorithms to optimize the charge/discharge of shared fleet vehicles for energy cost minimization. HNEI made significant progress across various project components under APRISES18. The completed activities include:

- Refinement of the web-based EV reservation system;
- Finalization of the autonomous control algorithm for optimized charge/discharge scheduling;
- Integration and development of the reservation system and control algorithms on the project server, alongside the development of a dedicated database for fleet operational data;
- Facilitated user adoption through comprehensive in-person user training sessions for HNEI employees and designated drivers from select UH departments;
- Thorough evaluation of the system performance and economic viability of the EV charge/discharge optimization algorithm;

- Economic analysis of alternative EV charging methods, including unidirectional charging with no intelligence, smart unidirectional charging, and bidirectional charging;
- Integration of a telematics system to monitor EV battery status while a vehicle is in on road operation;
- Research exploring various methods to estimate EV energy consumption to more accurately predict battery status for predefined trips; and
- Studies conducted to evaluate the feasibility of integrating EV chargers into the distribution grid.

4.1d) HNEI also continued efforts on the demonstration of an advanced Conservation Voltage Reduction (CVR) project in Okinawa, Japan. Under previous APRISES awards, control algorithms and communications between field meters and the CVR controller were validated in a hardware-in-the-loop test platform and the on-site construction was scoped and procured. Commissioning of the voltage regulator was delayed until March 2022 due to COVID-19 restrictions and the project faced several challenges due to failures of the PQube meters that were installed to measure the voltage at each transformer. While hardware and software issues continued to be an issue, HNEI's Grid***START*** team worked to resolve them and initiated detailed data collection and analysis.

4.1e) Monitoring transformer health is key part of ensuring a reliable power distribution system. Traditional methods often fall short, as critical component checks and fault prediction often involve manual processes. This can lead to unexpected breakdowns and shortened transformer lifespans. Under APRISES18, HNEI Grid***START*** developed an online assessment system powered by a fuzzy logic evaluation model to monitor transformer health. This real-time system quickly responds to varying inputs, monitoring transformer health with readily available measurements and avoiding the need for expensive sensors or operational disruptions. The system analyzes operational characteristics on a central server, recommending maintenance, reconfiguration, or replacement needs before issues arise. These insights are then seamlessly transmitted to operators. Ultimately, this low-cost and straightforward monitoring program promises reduced damage, enhanced grid reliability, improved transformer management, and informed maintenance decisions.

4.1f) HNEI was a sub-awardee to the University of Central Florida for a previous U.S. Department of Energy (DOE) project, Sustainable Grid Platform with Enhanced System Layer and Fully Scalable Integration. The objective of the project was to meet the long-term goal of designing highly scalable technologies for distribution systems to operate reliably and securely with extremely high penetration of solar photovoltaic (PV) systems. Under APRISES18, HNEI has continued to advance PV hosting capacity estimation method applications. The inherent stochastic nature of energy production by distributed PV resources, particularly at high penetration levels, causes issues on distribution circuits, e.g., voltage limit violations, voltage flicker, and increased transformer tap actions. This research endeavors to develop an automated and efficient method to assess and determine the maximum penetration of distributed PV for each distribution circuit within a utility's service territory, while maintaining reliable and quality service within the constraints of existing infrastructure and controls.

4.1g) In response to a request from Naval Facilities Engineering and Expeditionary Warfare Center, HNEI requested permission to use a portion of the funding under Subtask 4.1, Resilient Grid Systems to support a study to develop an understanding of the existing infrastructure of the Red Hill Tanks, and to develop a preliminary comparison of Energy Storage technologies that may be applicable for use within the Red Hill Tank volumes and associated infrastructure. Makai Ocean Engineering had previously analyzed energy storage technologies for the U.S. Navy, Report No. N62583-09RFTOP, dated 22 October 2012. This new study was conducted by Makai Ocean Engineering under contract to HNEI and included an updated review of those technologies from 2012 as well as other identified as potential for use at the Red Hill Site.

Under Subtask 4.2, HNEI conducted research in four main areas: a) the continuation of the development of non-invasive characterization methodologies for Li-ion batteries diagnosis and prognosis; b) the implementation of the approach with data driven methods; c) the study of relaxation patterns in batteries; and d) the evaluation of Prussian blue analogues for desalination batteries. Testing was conducted at HNEI's PakaLi Battery Laboratory on the University of Hawaiʻi at Mānoa campus. The results of this work is documented in numerous publications referenced in this report.

Under Subtask 4.3, HNEI subcontracted MKThink (a registered dba for Miller Kelley Architects), to further analyze the results of a study they had performed previously under other funding. In 2022, MKThink conducted a study to assess the dilution and spatial variability of carbon dioxide (CO_2) concentration in classrooms under a variety of physical configurations, occupancies, and ventilation configurations. Results showed some interesting trends based on air exchange rate and location of the exhaust vent compared to the fresh air inlet vent, but the project stopped short of reaching defined conclusions that could be used to manage air quality while minimizing energy use. The objective of this work was to further analyze the results of the previous work in order to provide additional guidance in the placement of ventilation systems and to identify possible methods to manage energy from HVAC while maintaining air quality, using CO_2 concentration as the proxy for air quality. The additional analysis focused on a subset of the original work including four inlet-exhaust location configurations and three different air exchange rates deemed to be within normal operating ranges of commercial HVAC systems. As expected, for the same vent configuration, the average CO_2 concentration tracked monotonically with the air-exchange rate, decreasing as the air exchange rate was increased. Computational fluid dynamic modeling of the various configurations also indicated that the average CO_2 concentration could differ substantially with different inlet-exhaust configurations even for the same air-exchange rates. This work provided strong indication that air quality could be significantly impacted (i.e. improved) by correct location of the exhaust relative to air-inlets, even at the same air-exchange rates.

Task 5, Advanced Materials, comprises of two subtasks that includes the development and testing of using forward osmosis technology for energy efficient water purification and the development of novel thin film materials (primarily $Cu_2ZnSn(S, Se)_4$: CZTSSe) for solar energy conversion using inexpensive and scalable liquid-based processing.

Forward osmosis, which uses the osmotic pressure of a concentrated draw solution to pull water at low pressure with subsequent recovery of the fresh water from draw solute, is considered one of the promising emerging technologies for energy efficient water desalination. However, the FO technology still remain challenged by a lack of practical draw solutes that have high osmotic pressure and can be regenerated efficiently at low energy cost. The goal of this work is to contribute to the development of advanced high-water flux and low toxicity draw solutes for forward osmosis water purification. Under Subtask 5.1, benchmarking testing using the commercial system with state-of-art draw solutes indicated high dispersion in water flux values and large deviation of the data from literature. Efforts were then focused on fabrication of an advanced FO testing system to enable accurate determination of water flux and improve the repeatability of the water flux measurements from the FO system. An advanced forward osmosis lab scale water purification system specifically tailored for HNEI research needs, entailed making major improvements to the original system, has now been fabricated. Specific improvements are summarized in the report. Following the fabrication of the system, water flux tests were performed using cellulose triacetate membrane, commercial draw solutes, and deionized water feed solution in order to establish baseline performance of the FO system. The iterative process of optimization of operating procedures and adjustments to system components resulted in improvement in accuracy and consistence of the water flux measurements from the FO system, in line with expected results in the literature. Future work will focus on the development and testing of new draw solute materials.

Under Subtask 5.2, efforts to were continued in the development of novel thin film materials for low-cost photovoltaic applications using scalable "printing" processing. This work continues previous ONR-funded efforts to develop novel thin film materials (primarily $Cu_2ZnSnSe_4$: CZTSe and $CuInSe_2$: CISe) for solar energy conversion using cheap and scalable liquid-based processing. With this approach, printable inks containing all the necessary components to form the solar absorber can be easily coated using high-throughput techniques, such as spin coating and inkjet printing. Initial efforts under this award focused on modifying the surface energetics of CZTSe Solar Absorbers via sulfur incorporation. While sulfur was incorporated into the films, little improvement in device performance was observed. It is unclear if the lack of improvement came from the dose of sulfur being too low, or from the formation of new surface defects with sulfur incorporation. Subsequent work was then focused on the development of new defect passivation methods using printed $CuInSe_2$ as test solar material. Under APRISES18, the research team at HNEI developed a novel technique to incorporate Al_2O_3 throughout the entire solar absorber, using $CuIn(S,Se)_2$ (CISSe) as test material. This incorporation was achieved by adding an aluminum source directly into the molecular ink used for the synthesis of the CISSe solar absorber. Power conversion efficiency (PCE) as high as 11.6% was measured on Al-CISSe solar cell devices, a value significantly higher than that measured on CISSe baseline cells fabricated with an identical process but without Al (PCE of champion cell: 8.3%). This work is continuing.

Task 6, Advanced Heat Exchanger Development, continued to support the development of high-performance thin foil heat exchangers. Under subcontract to HNEI, Makai Ocean Engineering has been developing Thin Foil Heat Exchangers (TFHX) for use in seawater-refrigerant, air-water, and water-water applications. In this report period, Makai advanced the TFHX design, reduced the TFHX fabrication time and cost; and added empirical thermal, hydraulic, and structural/mechanical performance data to the TFHX database. This work allowed for the use of new materials to expand capabilities and implement qualities control processes, while adding to Makai's expertise in the fundamental principles of laser welding and further understanding of the TFHX technology. Additional detail is provided in this report and in Makai's final technical report, available on the HNEI website.

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-18/.**