FINAL TECHNICAL REPORT

Executive Summary

Asia Pacific Research Initiative for Sustainable Energy Systems

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March 1, 2017 through March 31, 2022

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 N00014-17-1-2206, the Asia Pacific Research Initiative for Sustainable Energy Systems 2016 (APRISES16), 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 APRISES16 comprises research, develop, testing, and evaluation (RDT&E) of a variety of distributed energy systems and novel energy technologies. APRISES16 also included significant effort directed toward power grid integration using Hawaiʻi as a model for applicability throughout the Pacific Region. Areas of emerging energy technologies researched under APRISES16 included membrane-based energy systems (primarily fuel cells), battery systems, water and air filtration technology, hydrogen refueling technology, and novel printable photovoltaics. APRISES16 also included significant work in the area of biorenewable resources with activities in novel biocarbons, anaerobic digestion, and marine fuels; as well as continued work in the area of methane hydrates. Significant effort was also focused on alternative energy systems for electric power generation and integration into smart microgrids and energy efficiency technologies. Makai Ocean Engineering, under subcontract to the University of Hawaiʻi, 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 to provide overall program management and coordination, developed and monitored partner and subcontract agreements, and developed outreach materials for both technical and non-technical audiences. All subawardees completed the contracted work.

Task 2, Emerging Energy Technologies, included RDT&E in the areas of fuel cells, air and water purification technology, Li-ion batteries, hydrogen refueling infrastructure, and the development of new techniques for printable photovoltaic materials. Substantial progress was made in each of these areas.

Under APRISES16, HNEI continued its collaboration with the Naval Research Laboratory (NRL) supporting Northwest UAV (NWUAV), the licensee of NRL's stamped metal bipolar plate unmanned aerial vehicles (UAV) fuel cell stack design, as they moved towards commercialization of their first generation 1.5 kW fuel cell power system. During this reporting period, HNEI

continued to provide troubleshooting support as NWUAV implemented their own production line for in-house stack builds based on the NRL fuel cell stack design.

HNEI also continued efforts to complete the move from the Hawaiʻi Sustainable Energy Research Facility on Hawaiian Electric property to individual labs on the UH campus. With limited fuel cell test capability during this transition, efforts were focused on technology development, specifically novel transition metal-carbide catalysis and potentially lower cost electrolytes for vanadium flow batteries. During this period, HNEI developed a new electrochemical reduction method for production of high-concentration low-acidity vanadium electrolytes. Initial testing showed promising results.

In the area of Battery Energy Systems, HNEI, under this award, completed the characterization of Generation 2 commercial Li-ion titanate batteries under representative grid conditions, evaluated the impact on battery lifetime when electric vehicles (EV) batteries are used to support grid operation, progressed its models of battery packs lifetime performance including the impact of inhomogeneities in the batteries, and continued development of non-invasive characterization methodologies for Li-ion batteries. Testing was completed at HNEI's Hawaiʻi Sustainable Energy Research Facility prior to the move to campus. Key accomplishments are described in this report and in the 8 publications and 13 presentations resulting from the work.

Under Task 2, HNEI also progressed its work on filtration materials for those contaminants unable to be managed in-situ and for purification of water via forward osmosis (FO). Results include development of regenerative air filtration materials; fabrication of a test system for high-efficiency forward osmosis for water purification; and exploration of synthesis techniques for novel hybrid materials combining ionic liquids and ionic solids for high draw forward osmosis solutes. While the results from this study demonstrated the technical feasibility of photocatalytic regeneration of purification materials, results were not sufficiently promising to continue the effort under future awards. HNEI synthesized and characterized novel metallo-ionic liquids and molten salts using a syntheses strategy that combines ionic liquids and ionic solids presents opportunities to tailor the physico-chemical properties. Under future funding, we will optimize the FO system to enable accurate, long duration measurements and regeneration of draw solutes and evaluate commercial and HNEI-developed draw solutes for forward osmosis seawater desalination.

Task 2 also continued support for HNEI's Hydrogen Refueling operations system at the Natural Energy Laboratory of Hawaiʻi Authority (NELHA) fueling station site. Efforts included ongoing support for the commissioning of hydrogen production and compression equipment and hydrogen transport trailers. Finally, Task 2 also included a modest effort to continue the development of a novel low-cost printing process for the fabrication of electronic materials (primarily $Cu_2ZnSn(S,Se)_4$: CZTSSe) for solar energy conversion. While fully integrated solar cells made with this new technique reached power conversion efficiency up to 7%, the open circuit voltage of these cells was found to be approximately 250 mV lower than that typically measured on parent chalcopyrite solar cells (e.g., $CuInGaSe_2$, CIGSe). Work was initiated to identify the causes of the lower than anticipated open-circuit voltage.

Task 3, Biorenewable Resources, continued research supporting the development of novel high-carbon products exhibiting characteristics of having undergone transient plastic phase during formation; continued efforts to identify commercial partners for HNEI's novel anaerobic digestion technology; and continued the investigation into the storage and oxidation stabilities of DSH-76, CHCD-76, and their blends with F-76.

HNEI had previously reported that, using constant volume pyrolysis under moderate reactor conditions, the biomass feedstock is converted to a powdered, free-flowing biocarbon. During this period, a constant-volume reactor test bed was used to explore reaction conditions that resulted in biocarbons exhibiting characteristics of transient plastic phase during formation. Results from characterization of materials produced under this task resulted in a patent disclosure filed with the UH Office of Technology Transfer.

Under Subtask 3.2, a master design for the anaerobic system was completed to support transfer to industry. Efforts to identify a commercial partner for deployment have not, to date, been successful.

Under the third subtask, HNEI continued its investigation into the physicochemical properties and storage and oxidation stability of CHCD-76, SIP-76, and their blends with F-76. Under this award, two American Society of Testing and Materials (ASTM) methods, i.e. ASTM D4625 and ASTM D5304, were used to investigate the storage stability of these fuel samples. ASTM D5304 was also modified to determine the oxygen consumption rate of fuels. ASTM D2274 testing was conducted to study the fuel oxidation stability. Results are summarized in this report.

Task 4, Methane Hydrates, focused on three objectives: advancing our understanding of the environmental impacts of natural seeps and accidental releases of methane and other hydrocarbons in the deep ocean; exploring the feasibility of sequestering CO_2 in natural methane hydrate reservoirs; and continued promotion of international research collaborations on methane hydrates.

While previous research provided significant insight into the dissolution process of CH_4 bubbles in seawater, the majority of laboratory experiments have been performed using pure water and field studies have been conducted in seawater. Furthermore, laboratory experiments mainly focused on the effects of the hydrate film formation on the dissolving bubbles, and only a very small number of measurements have been made of the bubble dissolution rate under non-hydrate forming conditions. In consideration of these deficiencies, HNEI developed a facility and methods to measure the dissolution rate of CH_4 bubbles outside of the hydrate film forming regime. A description of the facility and preliminary data are reported.

Injection of CO_2 into methane hydrate reservoirs in sediment has been proposed as a means to destabilize the hydrate to release methane gas for energy, and to sequester CO_2 from the atmosphere. While the limited number of laboratory experiments suggests that the exchange proceeds too slowly to be viable at a commercial-scale, new theoretical thermodynamic analyses have indicated that gas mixtures of N_2 and CO_2 may improve the kinetics of replacement of CH_4 with CO_2 in hydrate deposits. In order to assess the feasibility of CO_2-CH_4 hydrate exchange for simultaneous methane production and carbon sequestration, experiments were performed. While the methane and CO_2 hydrate dissociation peaks were observationally separate, it was not easy to separate heat flows associated with each phenomenon. Further, the heat flows of methane hydrate dissociation were very irregular compared to previously performed methane dissociation experiments – possibly as a result of CO_2 hydrates forming concurrently with CH_4 hydrate dissociation. While this remains an area of interest, HNEI is unlikely to continue these efforts under future awards.

Task 5, Secure Microgrids, included a range of projects to develop, test, and integrate secure microgrid technologies into larger grid systems. Activities supported under this award included the Molokaʻi Dynamic Load Bank; a Bi-Directional EV Charging Demonstration Project; development of a Hawaiʻi Virtual Power Plant Demonstration; and the Coconut Island DC Microgrid.

In March 2015, Maui Electric Company, Ltd. (MECO) informed customers that the Molokaʻi grid had reached its system-level PV hosting capacity limit. In response, under previous APRISES awards, HNEI initiated a joint HNEI and MECO project, to deploy a custom controlled Dynamic Load Bank (DLB) as a practical, reliable, and inexpensive means to prevent the baseload diesel generators from operating below their minimum dispatch level, and enable the grid connection of significantly more rooftop PV on Molokaʻi island. In November 2018, following the load bank commissioning and implementation of the automated controls, the utility was able to add an additional 725 kW of distributed PV capacity to the system. Under APRISES15, HNEI and MECO conducted field tests to determine if the DLB was capable of meeting the demands of fast frequency response. Under APRISES16, this information was summarized and presented to MECO. While the capabilities of the DLB appear able to contribute in mitigating the impact severity of under-frequency events (e.g., avoid shedding a "kicker" load block in the Molokaʻi automatic under-frequency load shedding scheme), the existing BESS was delivering adequate grid-stabilizing dynamic response for effective system operation. It was determined that available engineering resources were inadequate to meet the substantial time and effort required to coordinate and tune the controls of the DLB with the existing fast-frequency responsive BESS on the island.

To tackle the complex optimization problem and demonstrate the use of bidirectional EV chargers, HNEI is developing and evaluating the performance of novel algorithms that optimize the charge/discharge schedules of shared fleet EVs under its EV Bidirectional Charging demonstration project. The novel EV charger control algorithms are intended to ensure that the shared vehicles are efficiently assigned and readily available for transport needs while simultaneously, the controls deliver ancillary power and energy services through intelligent EV charge and discharge commands. Major project activities completed under APRISES16 included: finalizing electrical installation drawings; developing a bid package for the final construction and field installation work; awarding the construction contract to a contractor; installation and connection of the EV charger system; and continued development of the overall architecture of the proposed control algorithm. Under future APRISES funding, the web-based car reservation software will be finalized with the testing and evaluation phases initiated.

The objective of the Virtual Power Plant Demonstration project is to analyze the tradeoffs and demonstrate the economic dispatch of numerous customer- and utility-side energy/power services from multiple combined behind-the-meter (BTM) battery energy storage system plus photovoltaic (BESS + PV) units. Under APRISES14 and 15, a new electrical service was installed to connect the BESS units to the MECO power system, permits were acquired, and final site and equipment inspection was completed by MECO to allow installation of four Sunverge Solar Integration Systems. Ultimately, it was determined that the Sunverge rulesets were too limited to allow the full, dynamic economic optimization desired for the project. For this reason, under APRISES16, HNEI designed and implemented a web-based method to utilize the existing Sunverge website to allow external optimization algorithms and software to monitor and control the units. HNEI also contracted Haleakalā Solar to install a metering box using HNEI's Advanced Realtime Grid Energy Monitor System (ARGEMS) to allow tests to begin. In a typical test scenario, HNEI plans to economically dispatch the four BESS + PV units according to the defined optimization problem and the time-varying load profiles of the four HVAC systems in conjunction with PV generation.

Coconut Island (Moku O Loʻe) is a 28-acre (113,000 m²) island in Kāneʻohe Bay off the island of Oʻahu and is home to the Hawaiʻi Institute of Marine Biology (HIMB) of the University of Hawaiʻi. As such, it is an ideal site for a renewable energy technology-based test bed, particularly representative of an isolated location vulnerable to energy disruption yet serving critical power needs essential to the research and educational mission of HIMB. 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. With the major components procured under APRISES15, HNEI applied APRISES16 funding to procure the balance of the microgrid system components and infrastructure installation, including the construction and build-out of a control room next to one of the buildings. HNEI also installed the major components of the system within the control room. Under future APRISES funding, HNEI will complete the installation and commissioning of the DC microgrid system and initiate the testing and evaluation phases of the research.

Task 6, Ocean Energy, supported two projects. Under subcontract to HNEI, Makai Ocean Engineering continued development of its thin foil heat exchangers; and in support of potential sea water air conditioning (SWAC) for Honolulu on the Island of Oʻahu, HNEI collaborated with the University of Hawaiʻi's Department of Oceanography to develop a thorough understanding of the baseline oceanographic conditions at the proposed site of the Honolulu SWAC system.

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 and, after resolving production issues, produced several full length plates; reduced both TFHX fabrication time and cost; and expanded TFHX pressure capacity and channel sizes and began geometric and mechanical characterization of the thermal, hydraulic, and structural/mechanical performance of these new combinations. This work added to Makai's expertise in the fundamental principles of laser welding and furthered understanding of the TFHX technology. Additional detail is provided in this report and in Makai's final report, available on the HNEI website.

The objective of the seawater air conditioning monitoring project, conducted in collaboration with the University of Hawaiʻi's Department of Oceanography, was to develop a thorough understanding of the baseline oceanographic conditions at the proposed site of the Honolulu SWAC system. At this time, the proposed SWAC plant for Honolulu will not be constructed as previously planned. Sampling and data collection for this SWAC monitoring project ended in December 2020.

Task 7, Energy Efficiency and Transportation included two activities in the area of energy efficiency and one focused on emissions from the conversion to electric vehicles. The two activities in energy efficiency were to support an efficient nano-scale microgrid at Ka Honua Momona (KHM), on Molokaʻi, Hawaiʻi, a not-for-profit organization that supports the local Hawaiian community in Molokaʻi, including operation of aquaponics; and design and test an adaptive lighting study conducted in collaboration with the California Lighting Technology Center at the University of California, Davis.

Under previous APRISES awards, KHM collaborated with HNEI to develop an online dashboard providing visualization of the energy use and renewable energy production of their off-grid energy system for community education purposes. Under this award, the KHM compound was used as a proof-of-concept site to demonstrate a control scheme to optimize battery use, reduce inverter losses, and utilize energy that is otherwise wasted when a battery system can no longer store additional energy due to capacity constraints. HNEI's objectives for this project were to develop a load shifting scheme to maximize utilization on a site whose load profiles have intermittent and varying loads and finite battery storage capacity; increase system utility by adding load dumps ("opportunity loads") to utilize more available energy; and to test a "smart" *predictive look ahead programming* control strategy to match solar generation with partitioned battery storage in order to minimize inverter standby losses. The project successfully demonstrated that small off-grid renewable energy systems can significantly improve the utilization of the available energy sources (specifically, solar photovoltaic energy) by eliminating unnecessary inverter standby losses and adding opportunity loads to utilize excess available energy that may not otherwise be captured due to limited battery capacity. Details are provided in this report and the associated final report for the project.

In the second energy efficiency project, HNEI collaborated with the California Lighting Technology Center at the University of California, Davis to demonstrate and test a prototype adaptive lighting system intended to save energy and provide additional security in an outdoor setting. Demonstrations were established at the University of Hawaiʻi at Mānoa and at a civilian U.S. Navy facilities site. Significant energy efficiency gains were achieved at both sites and a number of recommendations for incorporation of adaptive lighting into real-world sites were put forward. A technical report describing the project details and key findings is available on the HNEI website.

The last activity under Task 7 was an analysis to assess the impact on fossil fuel use and emissions with the transition from Internal Combustion Engine (ICE) to plug-in Electric Vehicles (EVs), in combination with renewable electricity generation on a remote, isolated power grid. As expected, results show fossil fuel use and CO_2 emissions decrease with more clean power on the grid and decreasing ICE numbers. Results specific to varying charge scenarios was not explored but is included in other climate change related analysis being conducted by HNEI.

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-16/.**