Hawai'i National Marine Renewable Energy Center (HINMREC)

Final Technical Report

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Table of Contents

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This work would not have been possible without the generous support of the Department of Energy's EERE and cost sharing partners: UH (State Funds); Hawaiian Electric Company; Maui Electric Company; Department of Business Economic Development & Tourism(State of Hawaii); Ocean Power Technologies (USA); OCEANLINX (Australia);Lockheed Martin, and; Energy Island Ltd. (UK). Partners in this effort include: Sea Engineering, Det Norske Veritas group's DNVGL, formerly Garrad Hassan America, Inc., the University of Washington, the technology and device developers, and numerous regulatory and resource agencies.

The authors would also like to acknowledge the complimentary funding efforts and collaboration of the US Navy (Naval Facilities Engineering Command), US Naval Sea Systems Command via the Applied Research Laboratory at UH (ARL-UH), and the US Office of Naval Research. For a comprehensive overview of ocean energy research and development at UH, this report includes many of these related efforts.

EXECUTIVE SUMMARY

This report summarizes activities at the University of Hawaii (UH) stemming from the establishment of the Hawaii National Marine Renewable Energy Center (HINMREC) in 2008. The report covers a total of eleven years of activity as a result of many no-cost extensions of this project. This was necessitated primarily by lengthy delays in wave energy converter (WEC) device deployment schedules at the Navy's Wave Energy Test Site (WETS). The bulk of the work documented here was performed between the start of the project when the contract was executed between the US Department of Energy (DOE) and the University in March 2009 and the end of 2015. Work since that time, through the end of the project in September 2019, was primarily in the form of remaining subcontracts with the University of Washington for acoustic measurements/analysis, Williwaw Engineering for data collection and analysis support, and Sea Engineering for ongoing at-sea support in the form of maintenance, inspections, instrumentation deployments (ADCPs, acoustic platforms), and other logistics work. These activities continue at WETS, now under Naval Facilities Engineering Command (NAVFAC) funding.

HINMREC was established to facilitate the commercialization of WEC devices and to accelerate development and testing of Ocean Thermal Energy Conversion (OTEC) technologies. HINMREC was housed at the Hawaii Natural Energy Institute (HNEI) of UH and had a primary objective of facilitating the development and implementation of commercial wave energy systems. In recognition of the high costs associated with at-sea testing and evaluation of WEC devices, it was deemed imperative that HINMREC seek ways to reduce costs to developers by providing key research support to these early-stage technologies.

The DOE tasked HINMREC with facilitating and accelerating the build-out of WETS, the nation's first grid-connected open water wave energy conversion test facility, located off Marine Corps Base Hawaii (MCBH) in Kaneohe, on the island of Oahu. An existing test berth developed by the Navy at 30m water depth formed the core of the new WETS facility, which was expanded to include test berths at 60m and 80m water depths. The environmental assessment (EA) for this expansion was completed by the Navy in early 2014, and the new berths were installed in September 2014 (moorings) and June 2015 (cables to shore). This provided the capability to simultaneously test up to 3 WEC devices, with a maximum power production for any single WEC of 1MW. This facility and HINMREC's support allows development and commercialization of wave energy technology by providing a testing infrastructure that allows technology developers to test, demonstrate and evaluate their WEC devices, and generate data in order to advance WEC designs toward commercial readiness. A recap of these efforts under DOE/HINMREC funds is provided in this report, including the ways in which this DOE-funded work transitioned effectively to Navy-funded tasks in support of WETS.

HINMREC collaborated with the NAVFAC to implement the full three-berth WETS, providing grid-connected test berths for WEC devices with power output up to 1 MW. A major HINMREC activity was supporting the NAVFAC team in this expansion of WETS. With input from HINMREC environmental studies, an extensive and lengthy EA effort was undertaken by NAVFAC, contracting with an independent environmental firm in accordance with the National Environmental Policy Act (NEPA). The EA resulted

in a Finding of No Significant Impact (FONSI) in February of 2014, allowing the expansion and operation of WETS to proceed. The EA means WEC developers do not have to obtain additional permits to test at WETS.

The 60m and 80m berth designs were completed in July 2014, and three-point mooring systems were installed in September of that year. Submarine power cables to shore were installed June 2015, and all shore infrastructure (switchgear, cabling, fiber routing, and refurbishment of Battery French bunker on MCBH) was completed that year. The design and installation of all WETS infrastructure was carried out under Navy contract to Sound and Sea Technologies, Inc.

WETS now allows for testing in water depths of 30m, 60m, and 80m. HINMREC’s primary role in the establishment of the full site was in the form of wave resource characterization and site survey, including bathymetry and bottom type for mooring system planning. Specifically, HINMREC commissioned Sea Engineering, Inc. to collect high-resolution bathymetric data within the WETS EA bounds, as well as detailed bottom type data, including sand thickness. As WETS is characterized by varying thickness of sand (from none to over 20m in some areas), a key was locating areas where sand thickness was suitable for the placement of large drag-embedment anchors included in the deep berth mooring design.

HINMREC’s role once the site was fully permitted in early 2014 was to begin independent WEC device power performance analysis and evaluation in support of deployed pre-commercial WECs and to monitor their acoustic and electromagnetic field (EMF) signatures once deployed on site. While EMF measurements were ultimately dropped due to non-availability of measuring systems and a growing acceptance that these impacts will be negligible for the anticipated levels of power production at WETS, many acoustic measurements were made by HINMREC and are now continuing under Navy funding. These essential roles of power performance assessment and environmental monitoring will be discussed in detail in this report and the associated subject area reports, journal publications, and presentations listed throughout.

The report also covers some related WETS activities supported by Navy funding, including significant efforts to outfit a site-dedicated support vessel, conduct mooring redesign and repair work after key failures occurred, and to conduct a second deployment of each of the first two WECs deployed at WETS – the Northwest Energy Innovations (NWEI) Azura and the Fred. Olsen Lifesaver.

Key findings of this work indicate that the wave regime at WETS is ideal to test, demonstrate and evaluate precommercial WEC devices, as well as wave energy as it applies to alternative markets. WETS is characterized by a robust year-round wave regime, driven by the dominant trade winds, providing excellent test conditions that are well suited to the state of the fledgling wave energy industry, and to testing of projects of relevance to DOE’s Powering the Blue Economy initiative. Further, the site experiences substantial winter swells from the north, as well as strong winter frontal systems that allow for assessment of WEC device and mooring survival in heavier seas – occasionally exceeding 5m significant wave height. Wave energy is considered early stage R&D, and many such projects are less well suited to test sites with more extreme conditions, such as the developing PacWave site in Oregon or the well-established Billia

Croo open-ocean test site run by the European Marine Energy Center (EMEC) in Scotland. Therefore, a key recommendation stemming from HINMREC's experience at WETS is that DOE continue to work with the Navy to support continuation of WETS beyond the currently planned FY2023 decommissioning.

A secondary objective in the establishment of HINMREC was to assist the private sector in moving ocean thermal energy conversion (OTEC) systems beyond proof-of-concept to pre-commercialization. This work was largely completed in the earlier years of HINMREC before the emphasis shifted primarily to supporting WETS. The technical role of the Center was primarily to focus on system and component engineering, and local and global investigations into the potential environmental impacts of OTEC systems. HINMREC was tasked with maintaining high-resolution models of ocean thermal resources and the potential sustainable power output of OTEC systems. Ongoing tests begun previously under ONR funding at the OTEC Heat Exchangers (HXs) Test Facility at the Natural Energy Laboratory of Hawaii Authority (NELHA), in Kona on Hawaii Island, have been continued to identify cost-effective aluminum alloys for use in OTEC systems operating in the corrosive marine environment. These studies will also be summarized in this report.

The report is organized according to the DOE tasking defined in the original award as follows:

1. Management
2. OTEC Resource Assessment and Sustainability
3. Wave Resource Modeling, Wave Field Measurements, and Data Analysis
4. Environmental Impact Monitoring at WETS
5. WEC Device Performance Analysis
6. Supporting Studies.

The work that has been accomplished under each of these tasks is described, including the initial objective, approach and accomplishments, challenges, impacts and resulting project changes, and results and deliverables. Further detail can be found in the publications, reports, and presentations listed in each task that were produced through these efforts and are available, or linked, on HNEI's website at https://www.hnei.hawaii.edu/publications/project-reports#HINMREC.

MAJOR ACCOMPLISHMENTS AND FINDINGS

TASK 1: MANAGEMENT

Later sections of this report will focus on specific project tasking related to HINMREC's efforts in OTEC, wave resource characterization, environmental monitoring, WEC performance monitoring and modeling, and some supplemental studies. This Task 1 section will cover numerous topics not specifically addressed in those sections in more detail, including some site development history and process, physical characteristics of the Wave Energy Test Site (WETS), outfitting of a site-dedicated vessel for WETS, and a high-level summary of the wave energy converter (WEC) deployments conducted to date at WETS. While not all of this work was specifically under HINMREC (DOE) funding, it is provided to give a more comprehensive account of WETS activities to date, with the intent to make clear to the reader which agency sponsored which related activities.

The Hawaii Natural Energy Institute (HNEI), at the University of Hawaii at Manoa (UH), has provided extensive project management throughout the duration of the HINMREC funding. In the first several years of the project, work focused on developing and facilitating partnerships between marine power system developers, utility companies, financing sources, engineering and environmental support companies, academia, government agencies, and NGOs.

Additionally, university engineering and science efforts were initiated to focus on industry needs, and DOD interest and funding was coordinated. The science and engineering studies included: advanced wave forecasting, numerical modeling of wave energy conversion devices, grid modeling, environmental impact studies, reliability and survivability, and corrosion and biofouling. A HINMREC website was established as a virtual center and repository for information developed through these efforts. Environmental studies and support to Navy permitting efforts at WETS were also initiated, along with identification of infrastructure needs for grid-connected testing. OTEC test facilities were enhanced at NELHA, working with industry to establish effective testing and validation of OTEC heat exchangers, and studies were initiated relevant to local and global OTEC resources and impacts.

At the outset of the program, three potential wave energy test sites were investigated in Hawaii. The northeast coast of Maui, about 1 km offshore of Pauwela Point was considered as a site to test wave power systems in collaboration with Maui Electric Company (MECO); to conduct environmental studies to assist WEC developer Oceanlinx’s permitting effort; and to leverage MECO investment in undersea infrastructure to expand for use by others. On Oahu, Makai Pier near Makapuu Point was investigated as a potential test site to obtain long term data series on the wave energy resource and other environmental parameters; provide an easily accessible site for the deployment and testing of small wave energy conversion devices and components; and to conduct research on corrosion and innovative materials. Also on Oahu, Marine Corps Base Hawaii (MCBH) at Kaneohe was explored and later determined to be the best site to develop a wave energy test site. This site was previously developed under ONR funding, and was intended to demonstrate the feasibility of wave power for naval facilities worldwide. Under ONR funding, the site was equipped with undersea power and fiber optic cabling to a single berth at 30m water depth. Ocean Power Technologies (OPT) began testing a single 40 kW buoy at a depth of 30m in June 2004, with the up and down motion of a float around a spar used to drive a generator and send generated power to shore via the undersea cable.

Also under ONR funding, an extensive Environmental Assessment (EA) was completed for the Navy by an independent environmental firm, in accordance with the National Environmental Policy Act (NEPA). This was for the purpose of expanding the site to include the two additional test berths – at 60m and 80m water depths. The EA was nearly a three-year effort, supported by HINMREC in the form of extensive site characterization, and resulted in a Finding of No Significant Impact (FONSI) in February 2014. HINMREC then supported the Navy's installation of WETS hardware, including the deep berth mooring hardware in September 2014 and the cables to shore in June 2015.

In more recent years, HINMREC has shifted primarily to supporting Navy, DOE, and WEC developer efforts to deploy and test WECs at WETS, beginning in 2015 with the NWEI Azura device. HNEI has supported WEC testing at WETS in three key ways: 1) environmental monitoring, 2) independent WEC device performance analysis, and 3) development of operational and maintenance protocols. The environmental monitoring program at WETS was designed to include device acoustic signature measurement, device and power cable electromagnetic fields (EMFs), and possible changes in device/mooring-induced sediment transport, seawater chemistry, and the ecological environment. (Ultimately, EMF was dropped as a focus due to a consensus that the likely levels of EMF at WETS would be insignificantly small. Some future EMF measurements may be made under separately funded DOE programs.) Independent device power performance for the devices deployed during the HINMREC era were conducted by measuring the incident wave field with two redundant Waverider© buoys (the first procured and deployed with DOE funds in October 2012 and the second with ONR funds in August 2016), and developing power matrices by collecting device power output for the length of the deployment. Wave and current measurements were also made with periodic deployments of an Acoustic Doppler Current Profiler (ADCP). In addition to power performance assessment, HINMREC also performed regular ROV and diver device and infrastructure inspections to monitor device and mooring system degradation, allowing creation of device-specific maintenance protocols. To support WEC deployments, numerical modeling efforts were also initiated, including both daily wave forecast modeling and hydrodynamic modeling of WEC performance.

A primary objective in the establishment of WETS was to reduce the considerable costs to developers associated with at-sea testing and evaluation of WEC devices. Providing regular device and mooring inspections are a key component of this support. Additionally, mooring design improvements and repairs were also found to be essential (more on this below), due to failures diagnosed during HINMREC inspections. Additionally, under NAVFAC funding, HNEI contracted with a local ocean engineering company to obtain and modify a support vessel intended as a site-dedicated resource. This vessel can be rapidly deployed to WETS and continues to be used under Navy funded work at WETS. Further, a limited amount of emergency maintenance response funding is provided to tenants at WETS, furthering HNEI's ability to fully document device reliability issues and develop operational and maintenance protocols for DOE and the Navy, while contributing to the fiscal unburdening of typically cash-strapped WEC developers. Developers remain responsible for major emergency responses, as well as WEC device deployment and recovery, but are financially aided by these funds. While the vessel outfitting and provision of maintenance support are through Navy funds, the recognition of these needs can be directly attributed to lessons learned through the execution of the HINMREC project.

The results and outcomes described in the subsequent Task sections of this report demonstrate extensive coordination provided by HINMREC management. In summary, management efforts involved oversight of numerous research activities within UH, oversight of multiple subcontracts, quarterly reporting to DOE, participation in DOE Peer Reviews, and extensive interaction with NAVFAC EXWC in the expansion of WETS from one to three berths, and in the transfer of site support functionality from DOE funds to Navy funds.

Management efforts have been focused on WETS for the past several years, with some OTEC studies continued under ONR funding. OTEC-related research, concentrated in the first several years of the HINMREC program, will be summarized in the next section. In terms of management, these projects involved providing guidance and direction to a number of UH researchers in varying fields of study of relevance to OTEC and overseeing those projects to completion.

In more recent years, the vast majority of effort under HINMREC funding was related to the establishment of WETS, and initial WEC testing at WETS. The major WETS activities that have commanded attention by HINMREC management are summarized in Table 1.1 below. Note that not all of these activities were conducted under DOE funds – many, particularly in the latter part of the table, were conducted with Navy funds, but are included here for the sake of presenting a reasonably complete sequence of major events at WETS. Navy funding has been directed to HNEI through the Applied Research Laboratory (ARL-UH). Developers that have tested their WEC devices at WETS include:

- Ocean Power Technologies (OPT) PowerBuoy® (prior to the establishment of HINMREC, and continuing into 2011, although without direct support provided by HINMREC or UH).
- Northwest Energy Innovations (NWEI) – Baseline Azura under DOE funds from June 2015 to December 2016, and Modified Azura under Navy funds through ARL from February to August 2018.
- Fred. Olsen, Lifesaver – First deployment under Navy funds, through Sound and Sea Technology, March 2016 to April 2017, and second deployment (with University of Washington AMP system integrated) under Navy funds through ARL from October 2018 to March 2019.

Each WEC deployment is covered in more detail below (under WEC Deployments). At the writing of this report, several additional WEC deployments are pending, including the Ocean Energy OE35 oscillating water column (OWC) device slated for the 60m berth in late 2020 or early 2021, the Oscilla Power Triton-C device slated for the 30m berth in that same timeframe, a smaller (1kW average) device from Columbia Power Technologies (SeaRay) in fall of 2020 (not at a test berth and not cabled to shore), a larger Columbia Power device (StingRay) at the 80m berth in 2022, Aquaharmonics WEC at 30m (following the Oscilla deployment at the 30m berth), and a grid-scale version of the NWEI point absorber WEC at the 80m berth, likely also in 2022. Others may follow, and/or be inserted into this rough schedule, depending on the future funding status of WETS and other programmatic developments at NAVFAC and DOE.

Table 1.1. Summary of major Wave Energy Test Site (WETS) activities.

Event	**Date(s)**	**Comment**
3 PowerBuoys® deployed at 30m berth	December, 2002-2011	Navy program, prior to HINMREC.
60 & 80m Berths: EA/FONSI	Issued February 2014	Navy funded ~ 3-year process
60 & 80m Berths: Final Design	Issued July 2014	Navy funded, aided by HINMREC surveys.
60 & 80m Berths: 3-point Mooring Systems	Installed September 2014	Navy funded install by Sound and Sea Technology (SST.
60 & 80m Berths: two submarine power cables	Installed June 2015	Navy funded, 9 months after mooring systems to make use of cable laying ship presence in Hawaii for other Navy jobs.
Azura baseline tests and performance data gathering at 30m berth	May 2015 to December 2016	Baseline Azura installation/operations under EA/FONSI, issued in 2003 for testing of six point absorbers: three already under OPT.
LifeSaver deployed at 60m berth, for tests and performance data gathering	March 2016 to March or April 2017	Not grid-connected, removed from WETS April 20, 2017.
80m Berth: unoccupied but two of three mooring lines failed	February 2016 (leg B-2) & December 2016 (leg B-1)	Mooring system failed before any device was deployed.
60m Berth: 1 of 3 mooring lines failed	February 2019 (leg A-1)	Similar failure to those observed at 80m berth.
60m & 80m Berth: Repairs	May/June 2019 completion for 60m berth, 80m berth repairs pending, anticipated in spring 2021.	ARL-UH contracted SST to conduct repairs. Extensive design support from DNV GL. Larger chain, pretension system.

The modified Azura, (with added heave plate and larger float), deployed (with Navy funds) at 30m berth.	February 2018 to August 2018.	Improved device motion, but no improvement in power due to PTO capabilities. Device scrapped in Honolulu.
Lifesaver re-deployed (under Navy funds) at 30m berth. UW AMP and WiBotic charging system integrated and received power from WEC.	October 2018 to March 2019.	Power Take-offs (PTOs) connected 6 days after deployment. Two-part installation sequence to allow for curing of rock bolt epoxy for PTOs. Device recovered March 2019, and due to weather, removal of remaining hardware completed April 2019.
60m Berth: Installation of mooring repairs, pull test, installation of no-WEC hawser.	May 2019 mooring repair installation, 8 June 2019 pull test, 22 June 2019 no-WEC install.	Operations broken into phases due to available weather windows.
60m Berth: Cable anchor modifications and bend-strain relief (BSR) replacement	November 2019 for 60m berth.	Necessitated by damage to BSR during original deployment and need to lighten anchor for future ops. Umbilical attachment hardware also changed.
80m Berth: Cable anchor modified.	Anticipated in spring/summer 2021.	Navy funded, same changes as at 60m berth.
Ocean Energy OWC deployed at 60m berth.	Anticipated spring 2021.	HINMREC planning. Device arrived in Hawaii December 2019; deployment delay due to damages in transit from Portland.

To disseminate findings, and as required by DOE, all findings have been documented using the Internet and through participation in appropriate conferences, meetings and presentations, publications in peer-reviewed technical journals, and other publications and reports. A HINMREC website was developed to serve as an information repository and has led to substantive working relationships with developers, US National Oceanic and Atmospheric Administration (NOAA), National Renewable Energy Laboratory (NREL), U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM), NAVFAC, Mexico, Spain, UK, Norway, American Samoa as well as sister National Marine Renewable Energy Centers. Content of the HINMREC website is being transitioned to the HNEI website and will continue to be available online at http://www.hnei.hawaii.edu/hinmrec/.

In HNEI’s management capacity with the HINMREC program, advice was provided to WETS tenants and interested WEC developers (e.g., Ocean Energy, Columbia Power, Oscilla, NWEI, Aquaharmonics, and others who expressed in interest in possible future testing at WETS), along with permitting, engineering, logistics, wave resource information, mooring design and repairs, and access to a Navy funded, dedicated support vessel. HINMREC also developed relationships and exchanged information with WEC and OTEC developers, the local electric utilities, and regulatory agencies, as well as guiding UH research to address the needs of developers and designers.

WETS Test Berth Development and Related Activities

The ultimate objective of this effort was to support development and commercialization of wave energy technology by providing open ocean testing infrastructure that allows WEC developers to prove their devices and generate the necessary data to advance their designs toward commercial readiness. HINMREC proposed expanding limited testing of single WEC devices located off MCBH in Kaneohe, Oahu in 2010 with the data, research, and initial experience from the HINMREC program, along with discussions with DOE, OPT and Navy.

WETS emerged as nearly ideal for early stage WEC device at-sea tests. The wave resource is well suited for testing, in that there is a robust wave regime year-round due to the consistent tradewind-driven waves, and maintenance, deployment and retrieval operations are feasible (though often require a substantial wait for ideal weather windows) at any time of year, (Figure 1.1). The wave resource is reliable year round, and is characterized by an annual average power flux of 10 to 15kW/m, with a significant number of events exceeding 40 kW/m (particularly in the winter months), as well as quiet periods providing year round access to WEC devices (Figure 1.2). Winter north swells and low-pressure system (storm) passages allow validation of WEC performance in more severe conditions to assess survivability. WEC devices can be tested in reasonably deep water without long power cabling to shore, and the MCBH bunker is situated on a hill close to shore, allowing for visual/camera observation and communications (direct line of site) without construction of a tower. MCBH is supportive of renewable energy development and has been an outstanding host to WETS activities. Additional advantages include: 1) Dive operations for inspections are enhanced by excellent underwater visibility in Hawaii, 2) the existing Waverider© buoys are supported by the PacIOOS infrastructure within UH, 3) University and locally-based private sector expertise in ocean engineering and oceanography are abundant, and 4) the test site is quite close (about 3.5 nautical miles) to a state boat harbor (He'eia Kea Small Boat Harbor), and readily accessible from staging areas in Honolulu Harbor and Pearl Harbor (within a day's transit - roughly 40nm distant). Short-term staging at the MCBH fuel pier and facilities at MCBH Waterfront Operations are also available to WETS activities, in coordination with appropriate personnel at the base.

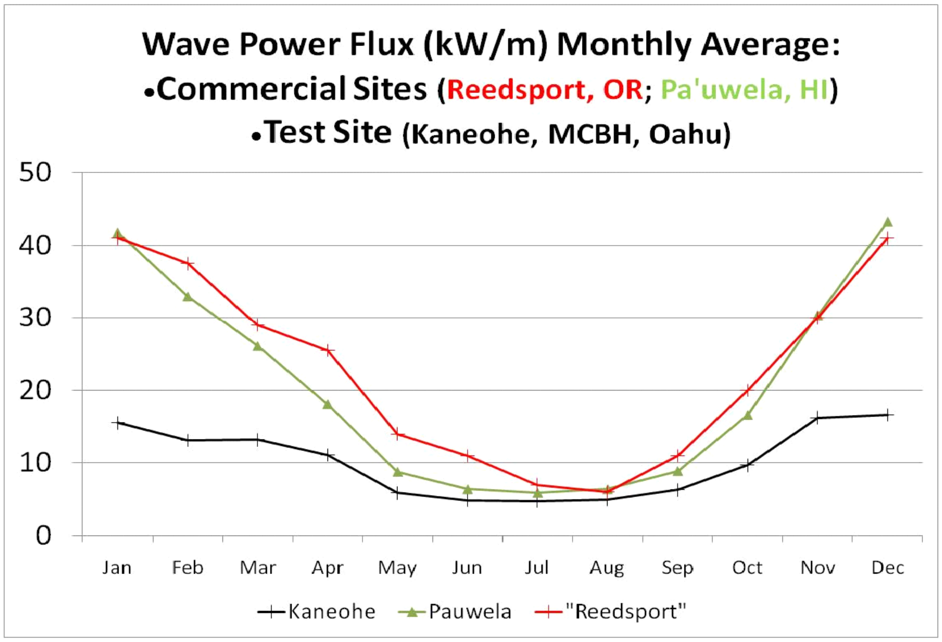


Figure 1.1. Monthly average wave power flux (kW/m) at WETS (black curve), as compared with two other potential wave energy testing/commercialization areas. The WETS regime allows year round deployment and retrieval operations, as compared with more severe offshore environments (such as Reedsport, Oregon and Pauwela, Hawaii).

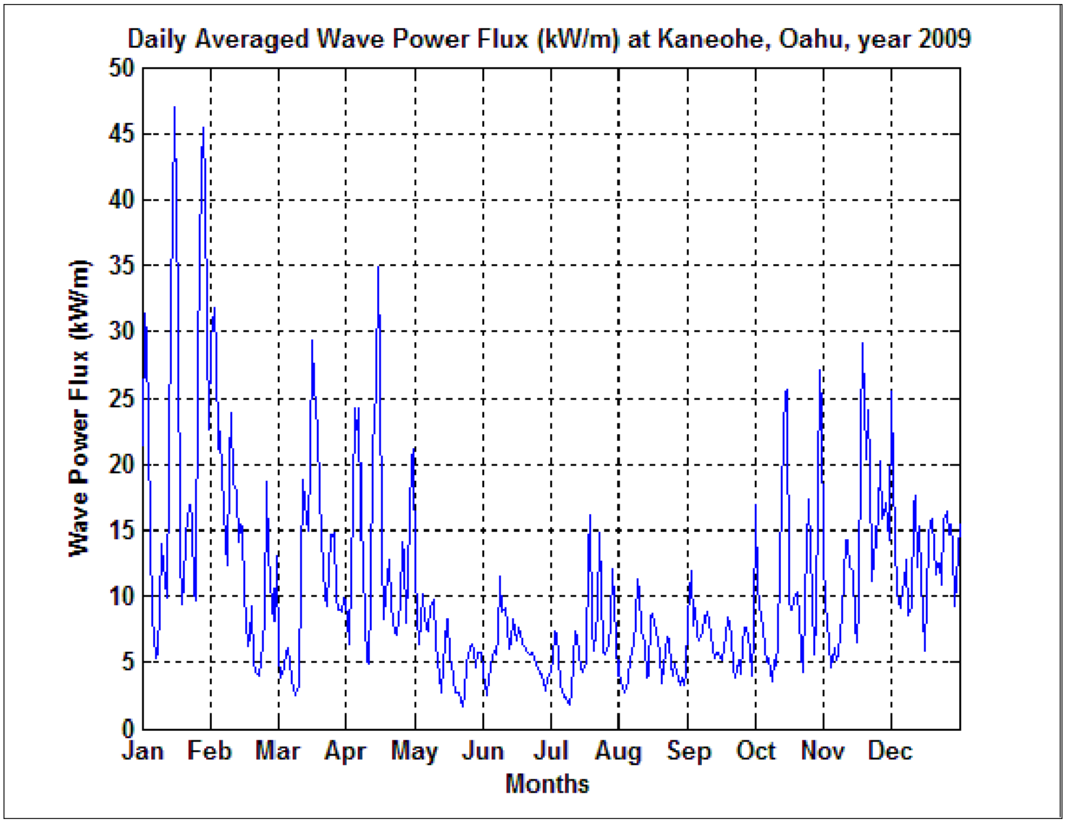


Figure 1.2. Daily wave power flux for a representative year (2009). WETS annual average power flux is 10 to 15kW/m, with significant winter events exceeding 40 kW/m, but quiet periods can occur throughout the year.

With these findings in hand, DOE tasked HINMREC with facilitating and accelerating the build-out of WETS – the nation’s first grid-connected open water wave energy conversion test facility. The concept was to expand existing facilities to provide multiple berthing for devices in the 100 to 500 kW (or more) range, in water depths ranging from 30m to 80m. Adding to the existing 30m test berth, two additional berths were ultimately planned, to provide simultaneous testing of up to 3 WEC devices in the 10 to 1000 kW range, at depths of 30m, 60m, and 80m. The final configuration of the site, including 3-point moorings at the two new deeper berths, is shown in Figure 1.3.

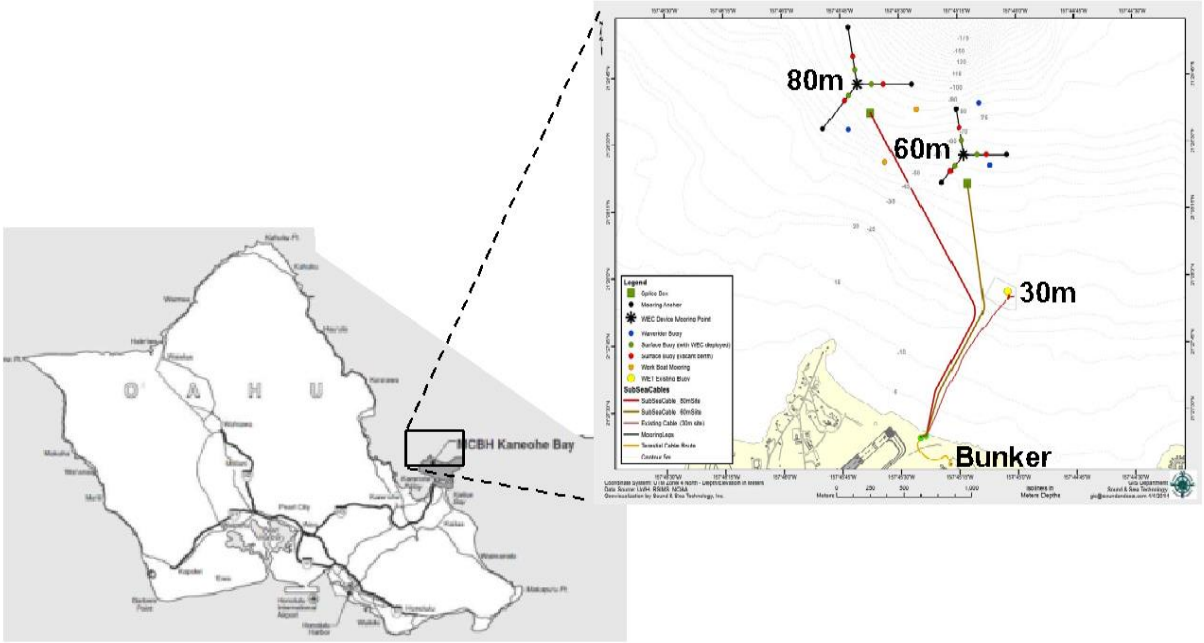


Figure 1.3. WETS mooring configuration and bathymetry map showing the three mooring sites at 30m, 60m, and 80m depth, along with the underwater power and communication cables (De Visser and Vega 2014).

HNMREC contracted with Sea Engineering Inc. to conduct site investigations in support of the development of the expanded test site. The surveys included multibeam bathymetry, side scan sonar, sub-bottom profiling and remotely operated vehicle (ROV) video. These surveys were completed in 2011 - reports are listed under Reports and Publications below.

The bathymetric survey was conducted using multibeam sonar systems to provide high-resolution water depth over the proposed WETS EA area. A sub-bottom profiling system, designed to provide information on sedimentary layers below the seafloor, was also used at the site. Key findings of the surveys included: reef limestone hard bottom is prevalent inshore of the 50 meter depth contour; a band of sediment, 5 to 12 meters thick and approximately 250 meters wide, is present at water depths of 55 to 65 meters; 1 to 2 meters of sand is typical from the 65 to 75 meter water depths; minimal sand is present in the eastern part of the project area seaward of the 75 meter contour; and there are barchan dunes in the northeastern corner of the site about 1-2 meters thick. Later bathymetric surveys revealed: the nearshore portion of the project area, between depths of 30 and 35 meters is relatively featureless and flat, with slopes ranging from 1V:34H to 1V:54H; a steeply sloping, irregular bottom is present at water depths between 35 and 45 meters, with slopes as steep as 1V:8H occurring between 40 and 45 meter water depths; between depths of 50 and 75 meters, the seafloor appears featureless, with little vertical relief, and typical slopes of 1V:25H; between depths of 75 and 85 meters in the northeastern corner of the project site, the bottom is relatively flat (1V:65H), and has barchan bedform features approximately 1.5 meters high, 150 to 200 meters long, and up to 100 meters wide, (barchans are arcuate, isolated dune forms, characteristic of an environment with a limited supply of sand); in the western portion of the site, at water depths deeper than 55 meters, the bottom slopes steeply into a pronounced submarine canyon. These characteristics are shown in Figure 1.4.

Following initial design analysis using the 2011 survey results, the WETS site was expanded 1000m to the west to accommodate the anticipated mooring footprint of the WEC devices. Additional bathymetry, sub-bottom and side scan surveys were completed to characterize and map the expanded area.

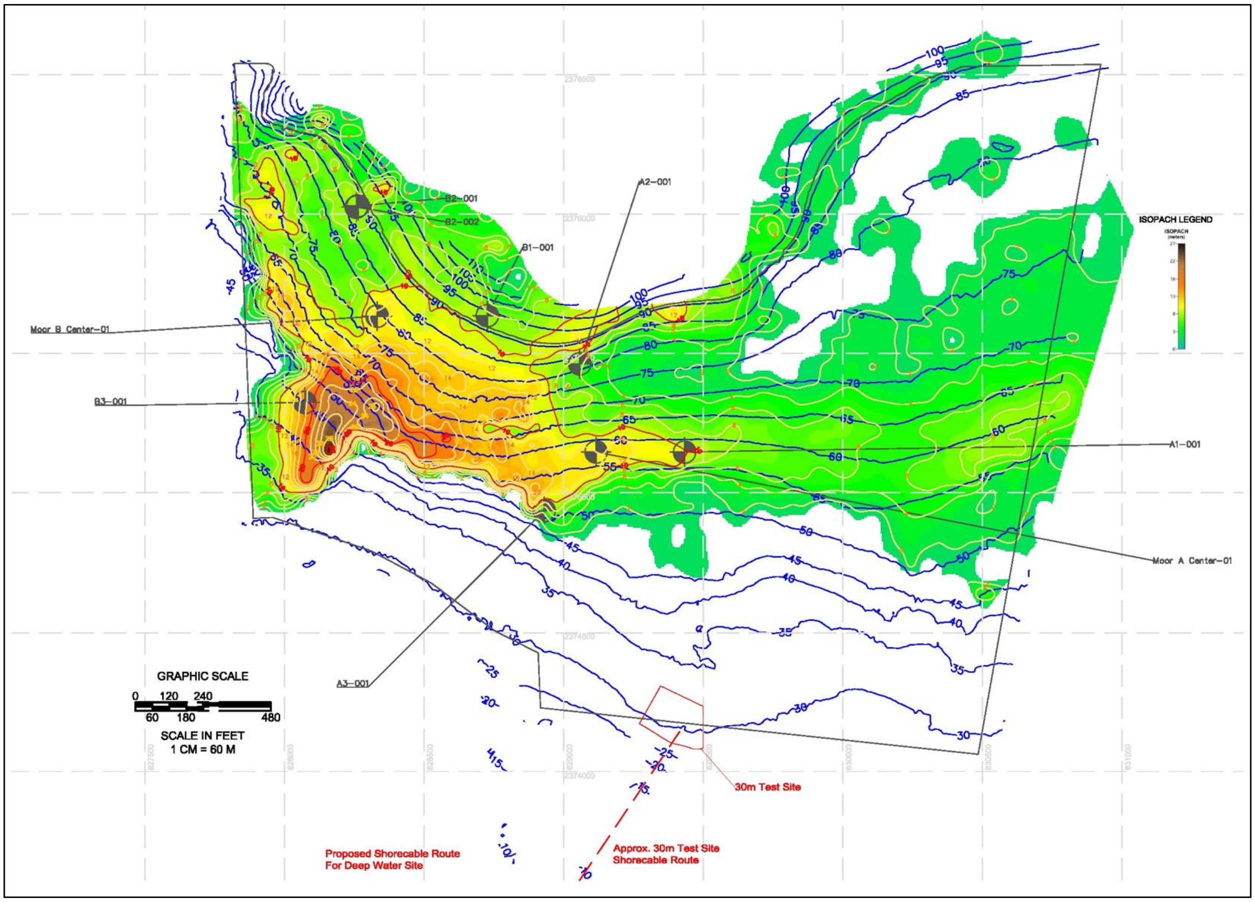


Figure 1.4. WETS bathymetry and sub-bottom profile data obtained by Sea Engineering, Inc., showing areas of thicker sand deposits suitable for placement of drag embedment anchors for the two new deeper berths.

In a collaborative effort led by HINMREC, and based on the bottom data collected by Sea Engineering Inc., the site designers for the Navy, Sound and Sea Technology (SST), were able to identify suitable areas of thick sand to support the emplacement of drag embedment anchors for the 3-point deep water moorings at 60m and 80m. The data were also used to identify cable paths that would minimize any impact on local coral ecosystems, resulting in the site layout (shown above in Figure 1.3).

In summary, the ocean bottom in the vicinity of WETS is a combination of rock, sand, and coral. A plot of the bathymetry and bottom composition, with yellow and red areas depicting thicker deposits of sand, is shown in Figure 1.5, with the final placement of the new 3-point mooring berths also shown.

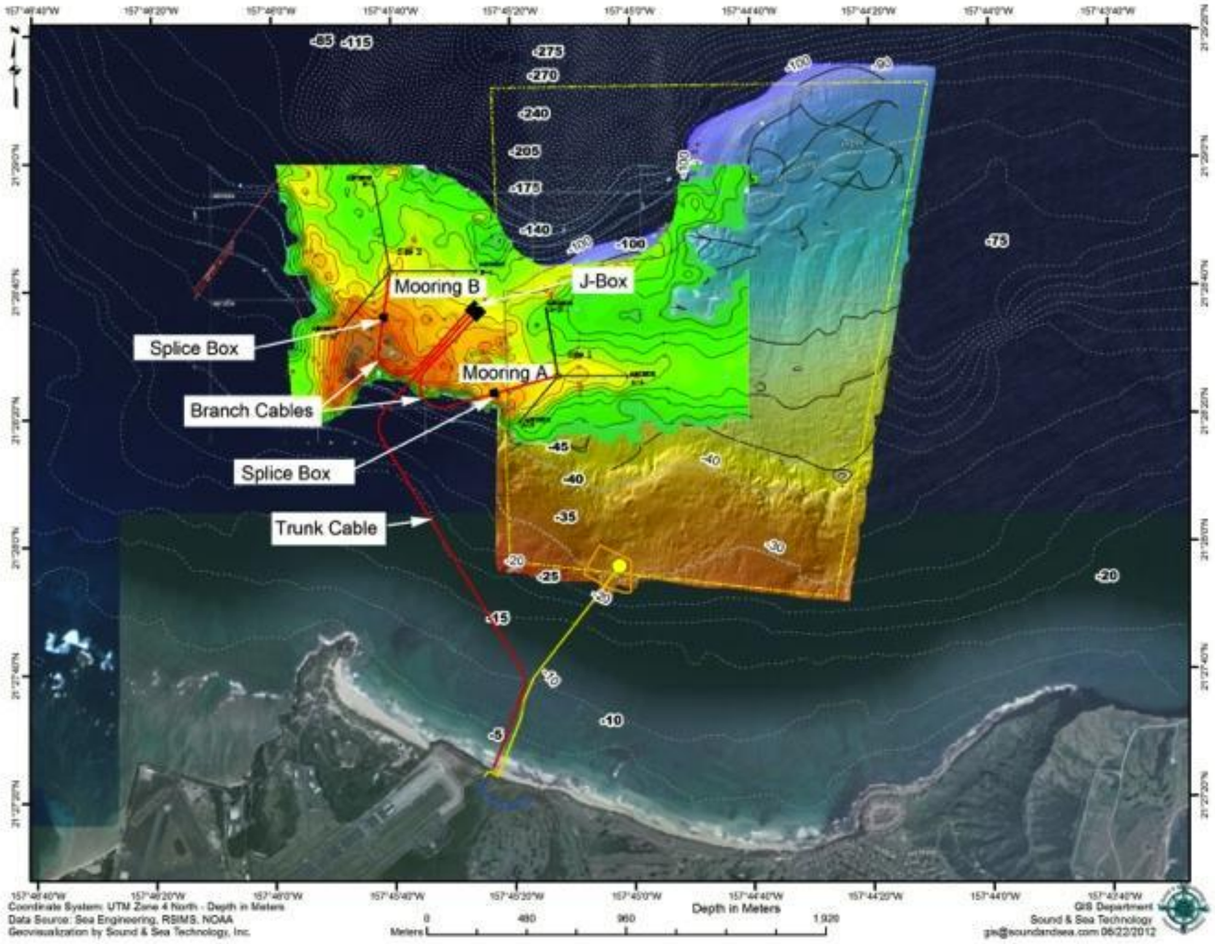


Figure 1.5. WETS bathymetry and bottom composition profile, with yellow and red areas depicting thicker deposits of sand, and placement of test berths, with deep water berths moored in areas of thicker sand deposits.

The pre-HINMREC 30m mooring berth also has a three-point mooring system (a tri-moor configuration). In this case, the only permanent hardware is the anchors themselves, with two rock-bolted wagon wheel type anchor bases and one large gravity anchor. These anchors are typically configured with risers that are connected to subsurface floats, with those floats in turn connected to a deployed WEC with a nylon (or other) hawser system. At both the 60m and 80m berths, the three-point mooring system consists of drag embedment anchors placed in sand as described above, heavy ground chain (with connected concrete sinker weights) leading to chain risers and three large surface floats. Figure 1.6 shows a schematic of a representative mooring leg for the 60m and 80m berths.

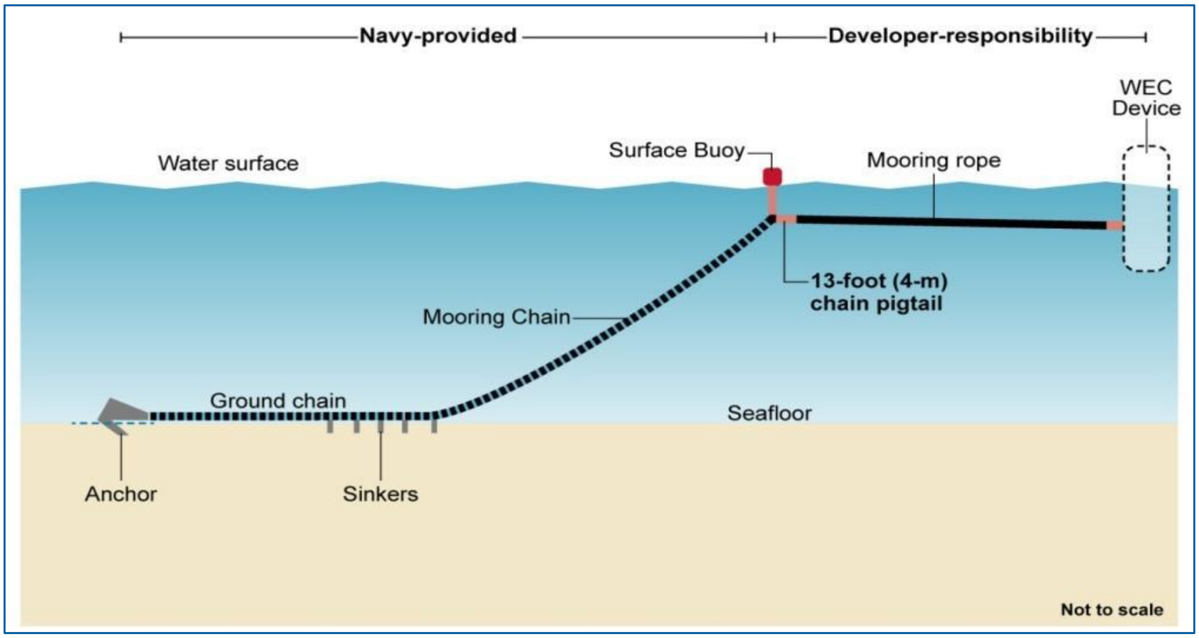


Figure 1.6. Schematic showing one leg of the three point mooring system used for WETS deep berths at 60m and 80m depth (De Visser and Vega 2014). Note: more recent modifications have reduced the number of sinker weights to two on each leg, and increased the weight of the riser chain (from sinkers to surface floats) for greater fatigue life.

At the preexisting 30m test berth, WETS provides access to the MCBH power grid, and thus to the Oahu grid, via a subsea cable with a maximum power transmission capacity of 250 kW at 4160 V. During the Navy-funded site expansion, two additional power cables were installed to service the 60m and 80m mooring berths, each able to transmit 1 MW at 11,500 V.

A nearby state boat harbor, He’eia Kea Small Boat Harbor on the north side of Kaneohe, lies to the west of WETS, about a 4-mile boat run from the site. It offers 54 moorings, 21 berths and 3 boat ramps. Honolulu Harbor, on the south side of Oahu, is more distant - about a 40nm boat trip - but offers a number of boat harbors and boatyards, where work on smaller WECs can occur. Limited drydocking facilities exist on Oahu, but these can be brought to bear for work on larger WECs, as is expected to occur with the 860-ton Ocean Energy OE35 WEC in the near future. Finally, NAVFAC EXWC, which serves as WETS Project Manager, has had success in arranging for dock space within Navy-controlled Pearl Harbor. Heavy lift capabilities have been utilized there previously, in the case of the Lifesaver initial launch and ultimate removal from the water, and a pier at Pearl Harbor’s Ford Island has been utilized for temporary berthing of Lifesaver and OE35. This may be an option with future WEC projects at WETS.

A major lesson learned over the course of the HINMREC support to the WETS effort has been related to mooring system design and survivability. Work in this area will be described in some detail later in this report in Tasks 4, 5 and specifically subtask 6.2, Alternate Mooring Designs, where major mooring repairs that have been designed and executed are described. A list of Report and Publications is included at the end of this task for more detailed information.

Site-dedicated Support Vessel

Under NAVFAC funding, HNEI contracted with Sea Engineering, Inc., a locally owned company, to purchase and convert a suitable seaworthy vessel intended as a site-dedicated resource. The vessel, a former Navy torpedo retriever 85 feet in length, was modified to extend its beam with the addition of two sponsons, and outfitted with dive and ROV facilities, an A-frame with 10-ton lift capacity, knuckleboom crane, a 4-point mooring capability, and ample workspaces for use by WEC developers and UH scientists and engineers. The vessel can be kept at the He'eia Kea state marina, or in Honolulu Harbor, and has the speed to be on site within an hour (if at He'eia Kea) or in about 4 hours from Honolulu. Lessons learned from the HINMREC site establishment and early operations at WETS were vital in determining the requirements for this vessel, which promises to serve the interests of wave energy testing at WETS for many years. The vessel, named Kupa'a, is shown in Figure 1.7.

Figure 1.7. Kupa'a, nearing completion for service at WETS in September 2019. A-frame and knuckleboom crane are visible, as are modified (wider) hull sponsons and expanded wheelhouse.

An important insight from testing WEC devices at WETS has been the frequent inability to safely conduct at-sea operations when lift capabilities are required. Operations are sea-state limited, which is made worse by the lack of heave compensation for winches on vessels routinely used (to date) at WETS. These vessels are cost effective, with daily rates ranging from $10,0000 to $20,0000, as opposed to the ~$100,000 required for vessels that include dynamic positioning (DP) thrusters and/or high-capacity heave compensated winches (e.g., Gulf of Mexico class). (This is important when considering WEC device testing at PacWave in Oregon, which is characterized by an annual average power flux of more than twice the value at WETS.)

To address this issue and maximize the utility of Kupa’a in a wider range of seastates when engaged in lifting activities, HNEI, under additional funding from NAVFAC, has implemented heave compensation into the 10-ton winch system on the vessel. As an example of the benefit of this system, without this added heave compensation, the A-frame and winch with 10-ton lift capacity is limited to significant wave heights (Hs) of less than about 0.5m for recovering the deep berth cable-anchor and suspended shore cable during WEC grid-connection operations. While routine maintenance and environmental survey operations requiring less lifting would be possible with the site-dedicated vessel in waves up to about 1.25m, the HNEI 34-year wave hindcast database indicates that 1.25m waves are exceeded at WETS about 80% of the time, while 0.5m waves are exceeded well over 95% of the time. Consequently, WEC developers would typically need to wait for extended periods to grid connect their devices, and HNEI’s routine research support will be feasible just 20% of the time.

Adding heave compensation to the vessel’s winch system is expected to significantly increase the number or workable days for various activities at WETS. Specifically, it was estimated that routine maintenance and survey operations would be possible up to Hs=2m (or roughly 75% of the time), and cable-anchor recovery up to 1.25 m (20% of the time), or possibly slightly higher. Following completion of the vessel modification, including incorporation of the heave-compensated winch system in 2019, a thorough analysis of the relative benefits of this added capability to support the types of work required at the Navy test site is planned. This research should provide valuable insights into potential cost reductions associated with optimizing ship size/instrumentation for future wave energy deployments.

WEC Deployments

Following is a summary of WEC deployments that HINMREC has been involved with to date - to varying degrees. Where funding is from Navy/NAVFAC, that is noted. However, in all cases highlighted here, the knowledge and experience gained from the HINMREC project have made direct contributions to outcomes in all WETS WEC deployments as successful as possible.

Oceanlinx

Oceanlinx, an Australian company, worked for an extended period to develop and install a WEC with a peak installed capacity of 500kW, off the north coast of Maui. It was to be situated approximately 200m north of Pauwela Point, several miles east of the international airport at Kahului. The technology was based on an oscillating water column (OWC), with bi-directional airflow driving a unidirectional air turbine. The project was being developed in collaboration with Maui Electric Company (MECO) and HINMREC, which supported in the form of resource assessment, permitting assistance, and other local coordination. Electricity from the project was to be fed directly into the MECO grid. Unfortunately, the project was ultimately cancelled because the Hawaii Public Utilities Commission did not approve related expenditures proposed by MECO. Regrettably, OCEANLINX declared bankruptcy, and the technology and intellectual property, brand and trademark were later sold.

Ocean Power Technologies

Prior to the HINMREC program, various iterations of Ocean Power Technologies’ (OPT) PowerBuoys® were tested at the 30m berth between 2002-2011 as part of a program with the US Navy to develop and test wave energy technology. The up and down motion of the buoy was used to drive a generator which was connected to shore via an undersea power cable to the original 30m test berth. The infrastructure implemented by OPT approximately one kilometer off the coast of MCBH has been incorporated into the WETS. OPT was funded by the Navy from September 2001 through December 2011.

The grid interface at the 30m berth was certified in 2007 by an independent laboratory, Intertek Testing Services. It is compliant with national and international standards, including the safety standards UL1741 and IEEE1547, and also bears the ETL Listed mark. Local Hawaii subcontractors did the installation, test, and servicing of the systems.

In September 2010 OPT completed the first-ever grid connection of a WEC device in the US at the MCBH in conjunction with the US Navy. The device was operated for one year. This connection demonstrated that WEC devices can be grid connected in a manner compliant with national and international standards. Between December 14, 2009 and the end of March 2011, it operated and produced power for 5,600 hours.

The system had numerous on-board sensors to monitor a wide variety of system performance variables, external conditions, and lifecycle parameters. Data collected by on-board computers was transmitted to a shore-based facility via a fiber optic cable embedded in the submarine power transmission cable, and then transmitted via the Internet to OPT's facility in Pennington, New Jersey. This significant deployment predated the University of Hawaii/HINMREC direct involvement in testing, and thus its role as an independent third party validator of power performance results.

HINMREC participated in an advisory role with OPT, including discussion of potential future testing at one of the deeper berths at WETS. This testing ultimately did not come to pass.

NWEI Baseline Prototype Azura

NWEI’s Azura, a point absorber WEC device, was deployed from late May 2015 to early December 2016 at the 30m berth for baseline tests and to gather performance data (Figure 1.8). The Azura generates energy from both the heave and surge motion of the wave, producing power from the relative motion between the hull (vertical spars) and the float, which rotates between the spars. Installation and operations were conducted under the original EA and FONSI issued in 2003 for the 30m berth, which allowed for multiple deployments of the WEC devices similar to the previous OPT devices. To deploy and operate the Azura for the full 18-month deployment, additional funding was required, which was made available through HINMREC, ONR, and NAVFAC.

Ultimately, the device deployment was quite successful, in that very little maintenance intervention was required over the 18-month period. Power was fed to the Oahu power grid in a first-of-its-kind grid-connected wave energy deployment in the United States that was validated by HINMREC/HNEI in a third party capacity. However, power performance was less than predicted, which led to the motivation to make modifications and redeploy the device, based on lessons learned from the first deployment.

Figure 1.8. Northwest Energy Innovations (NWEI) Azura WEC, during deployment in late May 2015 at the Wave Energy Test Site (WETS) 30m test berth. Sea Engineering’s vessel Huki Pau is seen, just after deployment.

NWEI Advanced Prototype Azura

Utilizing NAVFAC funding, HNEI contracted NWEI to modify the baseline Azura and deploy it for a second time, in hopes of improving power performance. Modifications consisted of the addition of a heave plate and a larger float with a longer moment arm. These modifications, shown in Figure 1.9, were intended to improve the relative motion of the float and spars, better aligning with the predominant wave conditions at WETS and enhancing electrical power generation. HNEI used additional Navy (NAVFAC) funds to contract Sea Engineering to deploy and retrieve the device. ONR funds were utilized to support the permitting process to get the Azura redeployed.

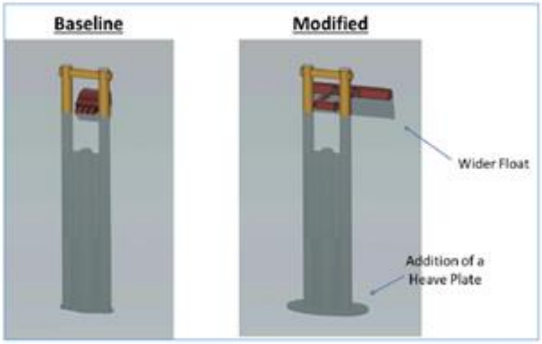


Figure 1.9. Baseline and modified Azura. Note addition of heave plate and modification of float.

The advanced device, shown in Figure 1.10, was deployed in February 2018 and was recovered in August 2018. The device again performed quite well in terms of durability, with essentially no maintenance activities required over the course of the 6-month deployment. However, expected power performance enhancement was not seen. This result prompted a thorough analysis of device performance by NWEI and HNEI, which has been documented in a collaborative conference paper (presented at the European Wave and Tidal Energy Conference - EWTEC 2019, Naples, Italy, "AZURA WEC power performance- a preliminary comparison of trial data and numerical modeling results", (see Task 5.2.2, for list of Reports and Presentations) - and a pending peer-reviewed journal article. In summary, the predicted improvements in device motions were validated, but did not translate into increased power production due the hydraulic power takeoff (PTO) being unable to accommodate the higher torque from the float at the frequency of the predominant wave motions from WETS. Funding was unavailable for further testing, but it seems likely that enhancements to the PTO to accommodate this high-frequency, high-torque motion from the device would have yielded significant improvements in device power performance.

Figure 1.10. Advanced Azura Prototype during an inspection by Sea Engineering at WETS in spring 2018. Note larger float with greater moment arm, as compared with baseline Azura.

Fred. Olsen Lifesaver

The Fred.Olsen LifeSaver device was deployed at the 60m berth in March of 2016 by Sound and Sea Technology under Navy funding, supported by HINMREC (Figure 1.11). Deployment was originally planned at the 80m berth but was shifted to the 60m berth due to an unexpected failure of one of the moorings legs of the 80m berth (more on this below in Tasks 4, 5, and Subtask 6.2). Further, the deployment was delayed for more than six months pending NOAA National Marine Fisheries Service (NMFS) permitting review and final Navy approval of the categorical exclusion (CATEX) permitting document. A key issue that held up the deployment was the potential impact of the mooring system on protected marine mammals, specifically a perceived entanglement risk to humpback whales. These issues were resolved in December 2015 (including a simplification in project scope), and the device was authorized for deployment at the 60m berth. Given the relatively infrequent availability of weather windows during the winter months, an opportunity for deployment of the device was not realized until late March 2016.

Figure 1.11. Fred. Olsen, Ltd. Lifesaver during deployment by Sea Engineering, Inc. in March 2016 at the WETS 60m test berth.

On March 25, 2016, the device was deployed and made operational. A six-month test phase was planned (e.g., April-Sep 2016), but a failure of one of three mooring lines occurred on May 21, 2016, causing the Lifesaver to shift away from its position in the center of the mooring, in turn placing large angles on the PTO winch lines and later causing them to fail as well. (Note: the other two mooring lines held, and the device was never fully detached from its mooring.) Electricity generation was reestablished in the summer of 2016, with two of three PTO lines operational. During September, a second PTO line failed, leaving only one PTO operational. Subsequently, all three PTO lines were replaced with new components.

Due in large part to these challenges with the moorings and PTO lines, the Lifesaver's planned six-month test phase was extended to a full year. It was recovered from the 60m berth in April 2017. To address the various issues relating to the moorings in the first deployment, HNEI worked with the Navy, Fred. Olsen, Sea Engineering, and the University of Washington (UW) to plan a second deployment. Motivations were twofold - 1) devise a mooring strategy that would be more reliable and would allow for improved device performance, and 2) integrate the UW Adaptable Monitoring Package (AMP), a suite of passive and active acoustic systems as well as optical systems for monitoring of marine life in the presence of marine energy converters, in such a way that the AMP would draw the power it needs from the WEC itself. The device was then deployed at the 30m berth (attaching the PTO lines to the seabed using a rock bolt system due to the rocky bottom at that berth, as opposed to using gravity anchors on the sandy seabed of the 60m berth) in October 2018, with the AMP integrated into the power system of the Lifesaver, and physically installed into one of two spare PTO wells in the hull (only 3 of 5 available wells were in use). PTO riser lines with less elasticity were utilized, and the storm mooring system was installed with reduced pretension as compared to the first deployment - both changes made in an attempt to improve power performance. The AMP integration included a wireless inductive charging system, from a Seattle company called WiBotic, of the sort that can be used to recharge autonomous underwater vehicles (AUVs). The device is shown in Figure 1.12.

From the mid-October deployment through the end of January 2019, the Lifesaver provided power to the AMP/WiBotic system nearly continuously, with a total uptime of 84%. On batteries alone, only about 1% uptime would be achievable. A much greater reliability in the mooring system was also achieved, although some problems did occur with the integrity of the rock bolts after about two months of deployment. A useful summary of both WETS Lifesaver deployments can be found at www.boltseapower.com, including power performance. The device was recovered in March 2019 and shipped back to the UK.

Figure 1.12. Fred. Olsen Bolt Lifesaver during second deployment at WETS. Note the UW AMP electronics enclosure (white box) and the above-water portion of the AMP instrumentation package. (The sensor head is approximately two meters below the water surface, but could be raised when the device is in transit to/from the site.)

Future WEC Deployments

As this report is written, WETS is in a period of infrastructure upgrade and device deployment planning. The years of HINMREC experience with the creation of the site and support to the early deployments at the site have directly translated into an ability for HNEI to seamlessly transition to directly supporting the Navy and WEC developers in projects going forward. At this writing, the following WEC device deployments are on our horizon - with rough estimates of deployment timing: Working closely with ARL, NAVFAC, and Ocean Energy, the Ocean Energy OE35 is expected to be the next deployment at WETS – at the 60m berth. The moorings at that berth, as well as the shore cable anchor, have been repaired and modified, and are ready to receive the device and its umbilical cable, with deployment expected in the summer of 2020. Other WECs expected at this writing over the next few years are:

- Oscilla Power Triton-C - 30m berth - early 2021
- Ocean Energy OE35 - 60m berth - spring 2021
- Columbia Power Technologies SeaRay - moored independently - early 2021
- Columbia Power Technologies StingRay - 80m berth - spring 2022
- Aquaharmonics - 30m berth - early 2022
- Northwest Energy Innovations (NWEI) Azura (grid-scale device) - 60m berth - spring 2022.

Reports and Publications

Technical Reports

Vega, L. January 2011. Biological Evaluation (BE) Effects of Bathymetric Surveys Required for Wave Energy Conversion (WEC) Testing Facilities Planned for Kaneohe Bay and Pauwela (Maui).

Sea Engineering, Inc., October 2011. Kaneohe Wave Energy Test Site Multibeam Bathymetry Survey.

Sea Engineering, Inc., November 2011. Kaneohe Wave Energy Test Site Sub-bottom Profiler Survey.

Sea Engineering, Inc., 2012. The Wave Energy Test Site (WETS) at MCBH, Kaneohe Diver Surveys Site 2.

Sea Engineering, Inc., February 2012. Kaneohe Wave Energy Test Site Remotely Operated Vehicle Survey.

Sea Engineering, Inc., March 2012. Geophysical Surveys of the Wave Energy Test Site (WETS) at MCBH, Kaneohe (summary of seafloor characteristics).

Sea Engineering, Inc., December 2012. The Wave Energy Test Site (WETS) at MCBH, Kaneohe, Diver Surveys Site 2 Report, (geophysical surveys of expanded WETS Site 2).

Sea Engineering, Inc., May 2013. The Wave Energy Test Site (WETS) at MBBH, Kaneohe Side Scan Data Report 2.

Sea Engineering, Inc., December 2013. Kaneohe Wave energy Test Site, Diver Survey Report (final deliverable).

Vega, L. et. al., 2014. Wave energy conversion and ocean thermal energy conversion potential in developing member countries, Asian Development Bank.

Sea Engineering, Inc., December 2014. WETS Task 3A Sediment Transport Analysis, (sediment staff deployment), Field Report.

Sea Engineering, Inc., July 2015. WETS Task 3B Sediment Transport Analysis, (sediment staff and scour piles), Field Report.

Sea Engineering, Inc., October 2015. WETS Task 3C Sediment Transport Analysis, (sediment staff and scour cylinders), Field Report.

Sea Engineering, Inc., April 2017. WETS Task 3D Sediment Transport Analysis, (sediment transport around existing structures), Field Report.

Conference Proceedings

DeVisser, A., Cable, B., Vega, L., June 2013. Wave Energy Test Site (WETS), Energy Ocean International, Providence, RI.

De Visser, A., Vega, L.A., April 2014. Wave Energy Test Site, proceedings of the 7th Annual Global Marine Renewable Energy Conference, Seattle, WA.

Cross, P., November 2014. University of Hawaii Research at the Hawaii Wave Energy Test Site, proceedings of the 2014 International Conference on Ocean Energy in Halifax, NS, Canada.

Cross, P., Rocheleau, R. Vega, L., Li, N., Cheung, K. F., April 2015. Early Research Efforts at the Navy's Wave Energy Test Site, 3rd Marine Energy Technology Symposium, METS2015, Washington, D.C.

Cross, P., U.S. February 2016. Navy Wave Energy Test Site – Research Update. Accepted presentation as part of a panel examining global marine energy test infrastructure, at the International Conference on Ocean Energy 2016, Edinburgh, Scotland.

Cross, P., Vega, L., Rajagopalan, K., Nihous, G., Li, N, Rocheleau, A., Anderson, P., August 2017. U.S. Navy Wave Energy Test Site – Early Findings. Reviewed paper submission to European Wave and Tidal Energy Conference, Cork, Ireland.

Li, N., Cross, P., May 2018. Statistical analysis of extreme wave conditions at WETS, awarded as best paper by the conference organizers, 6th annual Marine Energy Technology Symposium (METS), Washington, DC.

Rajagopalan, K., Cross, P., May 2018. Lifesaver mooring design, 6th annual Marine Energy Technology Symposium (METS), Washington, DC.

Cross, p., Rajagopalan, K., Druetzler, A., Argyros, A., Joslin, J., Hjetland, E., Stewart, A., September 2019. Recent Developments at the U.S. Navy Wave Energy Test Site. Reviewed paper to European Wave and Tidal Energy Conference, Naples, Italy.

Invited Conference Presentations

Cross, P., October 2013. Invited to attend, and co-authored presentation for workshop at European Marine Energy Center to celebrate 10-year anniversary of EMEC and discuss preparations at wave and tidal energy test sites internationally, Kirkwall, Scotland.

Cross, P., November 2014. HNEI Support at the U.S. Navy's Wave Energy Test Site, European Marine Energy Center-sponsored workshop on international wave and tidal energy test site developments, in conjunction with International Conference on Ocean Energy, Halifax, Canada.

Cross, P., July 2015. Invited by Oregon Wave Energy Trust to be on a panel (focused on the development of test infrastructure to support emerging marine hydrokinetic energy technology in the US), at the 2015 Hyrdrovision/Ocean Renewable Energy Conference. Portland.

Cross, P., April 2016. Invited by Department of Energy to represent WETS at International Marine Renewable Energy Conference (IMREC), as part of a panel on marine energy projects in the water in the US, (Vega., L. stood in), Washington, DC.

Cross, P., September 2016. Stood in for NAVFAC WETS Project Manager to deliver a lunch seminar at ORE, discussing the various environmental data collection efforts underway, and planned, at WETS. Portland, OR.

Cross, P., September 2016. Invited by Virginia Tech organizers to present an overview of WETS research activities at the 11th Annual Energy Harvesting Workshop, Arlington, VA.

Cross, P., September 2016. Invited by Oregon Wave Energy Trust to participate in a panel discussing marine energy test infrastructure at the Ocean Renewable Energy Conference (OREC). Portland, OR.

Cross, P., September 2017. Invited by Oregon Wave Energy Trust to participate in a panel discussing DOD efforts in marine energy at the Ocean Renewable Energy Conference (OREC), in Portland, OR.

Cross, P., May 2018. Invited by International Marine Renewable Energy Conference organizers to discuss WETS in-water developments at their conference, Washington, DC.

Cross, P., June 2018. Invited by Hydrovision 2018 organizers to discuss WETS in-water developments, lessons learned, and supply chain issues at their conference, Charlotte, NC.

Cross, P., September 2018. Invited by European Marine Energy Center to provide two talks – a WETS update and a summary of WETS environmental collection efforts – at the International Wave and Tidal Energy Research Sites (WaTERS) workshop, which preceded the Asian Wave and Tidal Energy Conference, Taipei, Taiwan.

Cross, P., September 2018. Invited by Pacific Ocean Energy Trust to participate in a panel assessing the suitability of existing marine energy test infrastructure to advance marine energy as applied to maritime markets (as opposed to grid-connected applications) at the Ocean Renewable Energy Conference (OREC), Portland, OR.

Cross, P., October 2019. Invited by European Marine Energy Center to provide an update on activities at WETS at the International Wave and Tidal Energy Research Sites (WaTERS) workshop, held in Stromness, Orkney Islands, Scotland (EMEC offices).

Other Presentations

Vega, L., February 2011, Expansion of Existing Facility into Wave Energy Test Site (WETS) Marine Corps Base Hawaii (MCBH), briefing to DOE.

Cross, P., November 2015. Invited to give a talk about WETS and wave energy, while in Norway to visit a wave energy test site, at NIVA – a Norwegian water research institute, Oslo, Norway.

TASK 2: OTEC RESOURCE ASSESSMENT AND SUSTAINABILITY

The concept of Ocean Thermal Energy Conversion (OTEC) has fascinated many generations of engineers since it was formulated by d’Arsonval in 1881. It hinges on the possibility of producing mechanical work (and, subsequently electricity) by exchanging heat with a warm reservoir of surface seawater and a cold reservoir of deep seawater in suitable tropical areas. While the basic heat engine technology at the heart of OTEC can be found in every thermal power plant today, practical seawater temperature differences of the order of only 20 C have made OTEC implementation very challenging. With thermodynamic efficiencies of about 3%, OTEC cycles must compensate with seawater flow rates as large as several cubic meters per second per megawatt of net electricity produced. This and other difficulties typical of deepwater marine environments have so far prevented OTEC from being economically competitive. Interest in this renewable technology has been sustained, however, with a growing worldwide energy demand, the prospect of declining fossil fuel reserves and serious concerns about climate change.

The main characteristics of OTEC relevant to the HINMREC study of OTEC resources are the high seawater flow rate intensity mentioned earlier and the sensitivity of OTEC power output to changes in available seawater temperature differences. Unlike many intermittent renewable technologies, OTEC is capable of baseload electricity production in favorable regions. Yet, a variation of 1^{o} C in the seawater thermal resource corresponds to a change in net power output on the order of 15%. The combination of large flow rates and temperature sensitivity suggests that a very dense deployment of OTEC systems might result in self-limiting power production. Under this scenario, OTEC resources would actually have a maximum. This was shown to occur in very simplified one-dimensional models of the water column with OTEC. The situation could be compared to the case of a hydroelectric power plant where excessive water flow rates would diminish the existing head. In the case of OTEC, however, there is no obvious flow rate scale a priori. The following journal articles, with high-level summaries given here, provide an overview of detailed modeling efforts carried out under HINMREC support for global OTEC assessment.

1) Rajagopalan and Nihous (2013a)

The main objective in this study was to explore the possibility of using state-of-the-art ocean general circulation models (OGCMs) in estimating global OTEC resources. In order to limit the computational burden of this undertaking and simplify the comparative interpretation of results with available 1-D OTEC resource estimates, a relatively coarse spatial resolution and standard (or default) parametric choices were made for the targeted OGCM calculations. In addition, features of the modeling protocol that specifically define OTEC operations and power production followed those proposed in the past. Given the complexity and broad spatial variability of oceanic circulation and temperature fields, even such preliminary numerical experiments are expected to yield more accurate and more reliable results than previously obtained in other studies.

The numerical tool selected for this study was the general oceanic (and atmospheric) circulation model MITgcm developed at the Massachusetts Institute of Technology. MITgcm can represent oceanic and atmospheric phenomena over a wide range of scales by discretizing the transport equations for momentum, potential temperature and salinity (specific humidity in the case of the atmosphere) with the finite-volume technique. MITgcm is configured to simulate the global ocean circulation on a relatively coarse 4^o x 4^o (horizontal) grid. The MITgcm solver was modified to incorporate fluid sinks, as well as temporally varying temperature and salinity source characteristics that can be dynamically specified. These changes were required to properly represent OTEC intakes of surface and deep seawater (sinks) as well as an OTEC mixed effluent discharge (source). First, basic tests were carried out with the MITgcm model (without OTEC sources/sinks) to establish that the temperature drift is minimum, there is closure on the heat budget, and that the MITgcm model prediction of thermohaline circulation agrees well with observations.

The criterion established for implementation of OTEC globally is that any monthly average temperature difference between 20m and 1000m water depths always exceed 18^o C. The global ocean thus selected is shown in Figure 2.1. OTEC operations are represented in the OGCM by the inclusion of mass flow singularities of given strengths. Two sinks depict the intake of seawater in the surface layer and at a water depth of 1000 m, respectively, and one source describes the release of mixed effluents in the water column.

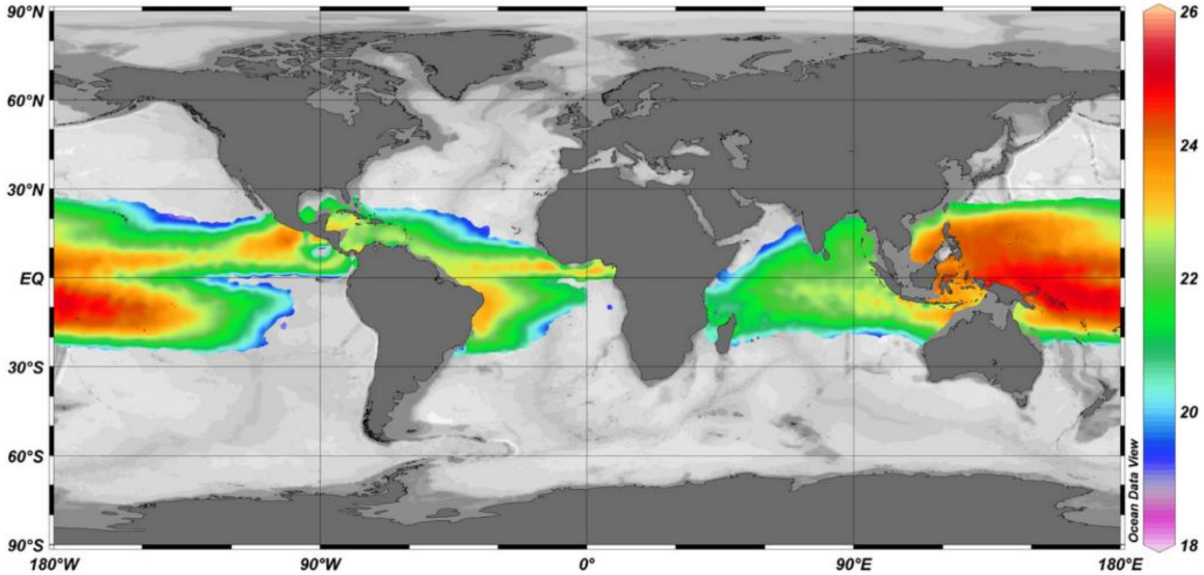


Figure 2.1. The OTEC region defined from the quarter-degree World Ocean Atlas 2005 database. (color scale: mean annual temperature difference between water depths of 20 m and 1000 m)

The ratio γ of OTEC surface seawater flow rate over OTEC deep seawater flow rate is fixed at 1.5, a value greater than one typical of OTEC system optimizations. As a result, the strength of all OTEC flow singularities can be quantified by the deep seawater value Q_{cw} alone. Furthermore, Q_{cw} can be expressed as an equivalent vertical velocity w_{cw} if it is divided by the horizontal grid cell area. In this study, constant values of w_{cw} across the OTEC region serve as a basis for specific MITgcm runs. Because OTEC flow rates (per unit horizontal area) are therefore uniformly distributed, the parasitic pumping power density P_{pump} is a constant. Using w_{cw} also allows a connection to the historical notion of upwelling (vertical advection) rate used in early descriptions of the global oceanic circulation. In 1-D studies of OTEC resources, the value of w_{cw} for which OTEC net power production would peak was found to be of the same order of magnitude as the background upwelling rate.

In Figure 2.2, results from the 4^o x 4^o MITgcm model are given. They are the focal point of this article.

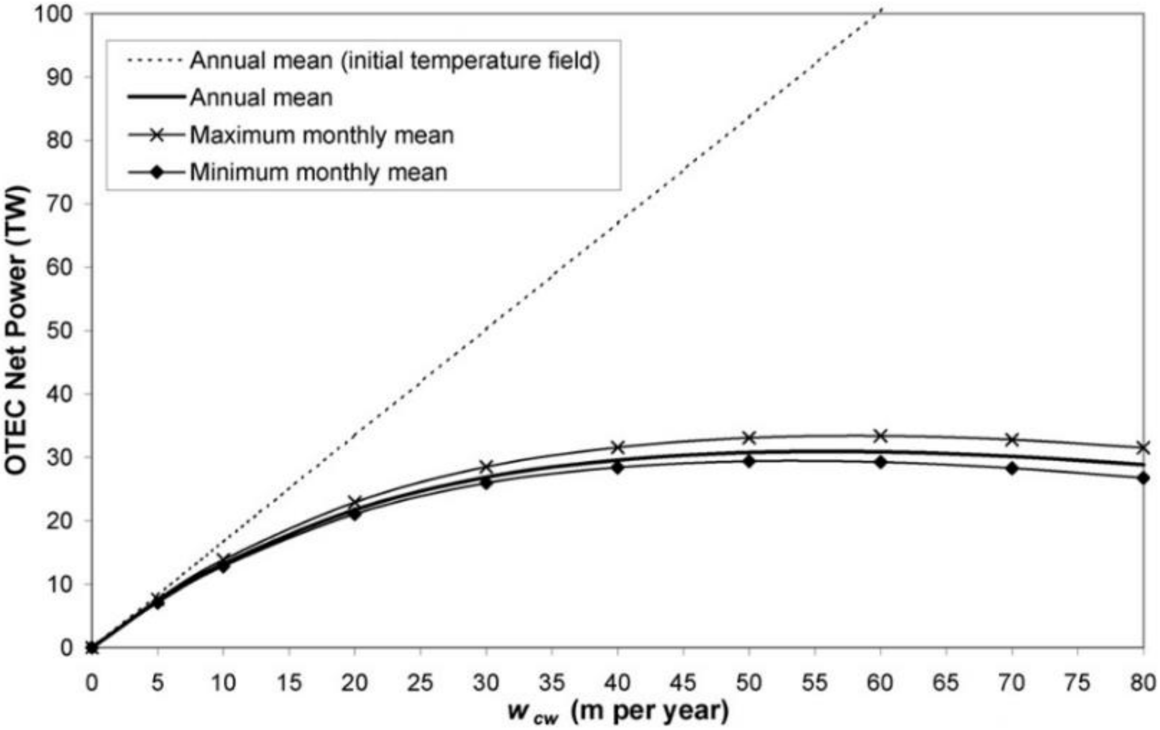


Figure 2.2. Global OTEC net power as a function of deep seawater vertical velocity w_{cw}

The OTEC net power maximum of 30TW is achieved. This is an order larger than the 3-5TW predicted with the simple 1-D model. Notwithstanding the complexity of the more sophisticated model (MITgcm), this discrepancy should be expected since horizontal transport phenomena in the ocean dominate their vertical counterparts, especially where density stratification is strong. In a 1-D model reduced to a vertical water column, the lack of adequate horizontal transport mechanisms would amplify the effect of OTEC flow perturbations on the vertical thermal structure. Consequently, any significant degradation of OTEC net power production would occur at smaller OTEC flow rates in such a limited modeling context.

With large-scale global OTEC operations (hundreds of thousands of 100MW plants), much of the heat transferred from the atmosphere to the ocean in tropical regions would be transported horizontally elsewhere before the local temperature stratification could be adversely affected. It is noteworthy that the cooling of the tropical oceanic mixed-layer, which is the driving mechanism for an induced heat flux from the atmosphere to the ocean in tropical areas, is predicted to persist in the present model. In 1-D analyses, mixed-layer cooling under large-scale OTEC scenarios is a transient phenomenon instead. A persistent tropical surface cooling would be balanced by a warming trend in the higher latitudes and in regions of strong coastal upwelling, the extent of which may set practical environmental limits to massive OTEC deployment. The large OTEC flow rates corresponding to maximum net power production are also shown to significantly boost the oceanic thermohaline circulation (THC). In the Atlantic, for example, the THC would essentially double from about 15 Sv. In simple interconnected 1-D approaches, large OTEC flow rates do not permanently affect the THC. The work described here is believed to represent an important step toward a better quantification of OTEC resources using state-of-the-art numerical models of the ocean. Many aspects of the OGCM runs performed in this study are subject to improvement, refinement and critical evaluation. In particular, the effects of grid resolution, model parameterization and level of coupling between the ocean and atmosphere deserve to be investigated. Some of these improvements were implemented and reported in the following HINMREC-sponsored study.

2) Rajagopalan and Nihous (2013b)

In **1)** above, the question of global OTEC resource was tackled for the first time with state-of-the-art ocean general circulation models. A relatively coarse numerical grid was adopted to limit the numerical burden of the proposed simulations, i.e. 4° x 4° horizontally, with 15 vertical layers including a 50 m thick surface layer. The existence of a maximum for global OTEC net power production was confirmed. At 30 TW, this maximum would be about ten times that predicted in earlier one-dimensional studies. Such a result demonstrated the importance of fast horizontal transport phenomena, not accounted for in one-dimensional models, in slowing the local erosion of the water column’s thermal stratification as OTEC flow intensity increases. It was also revealed that a cooling of the surface layer in the OTEC region could be sustained as long as warming occurs elsewhere. Although this work represents an important step to more accurately assess interactions between the environment and a very large number of OTEC systems deployed throughout the tropical seas, significant improvements in OGCM computational and physical resolutions were made in the work described here.

Numerical resolution was increased to 1deg x 1deg, and the number of vertical layers was also increased to 23, with the topmost layer now 10m thick. The choice of thinner layers toward the surface allows a better representation of enhanced vertical stratification in the upper part of the water column. Since the horizontal resolution was increased to 1deg, many of the fluxes required to force the model needed to be recalculated. The model is forced with several monthly averaged fluxes specified at the ocean-atmosphere boundary. Meridional and zonal wind-stress fields were obtained from a well-known database, NOAA Atlas. The other inputs are heat, short-wave radiation, and freshwater fluxes. Their specification required a delicate two-step process. At first, essential flux components were either directly found or determined from extensive parameterizations; these include the short-wave radiation, long-wave radiation, latent heat, sensible heat, evaporation, and precipitation fluxes. Some intermediate fields were available elsewhere, such as the short-wave radiation under clear skies and the surface albedo. In the simulations, two important constraints had to be satisfied for the OGCM to run properly: that the annual averages of the heat and freshwater fluxes integrated over the entire ocean surface both be zero. Simply using available or calculated data generally fails to approximate such constraints to an acceptable degree. In the absence of continuous data assimilation, small inaccuracies in surface input fluxes can lead to large drifts in calculated fields over long enough simulation times. The methodology adopted here was to multiply key terms in the heat and freshwater fluxes by unknown tuning parameters (of order one). The seven selected parameters were then determined by minimizing the normalized sum of the yearly averaged heat and freshwater fluxes integrated over the entire ocean surface. This operation was performed with a standard multidimensional downhill simplex method implemented in the MATLAB function fminsearch. A low threshold of 0.9 was also imposed on the tuning parameters, which ended up ranging from 0.91 to 1.09.

Basic checks were performed on the MITgcm model to establish that the temperature drift is minimal, and the model predictions of THC agrees with published data. Following these basic checks, the OTEC scenario was implemented in the MITgcm model. The results for global OTEC net power are shown in Figure 2.3.

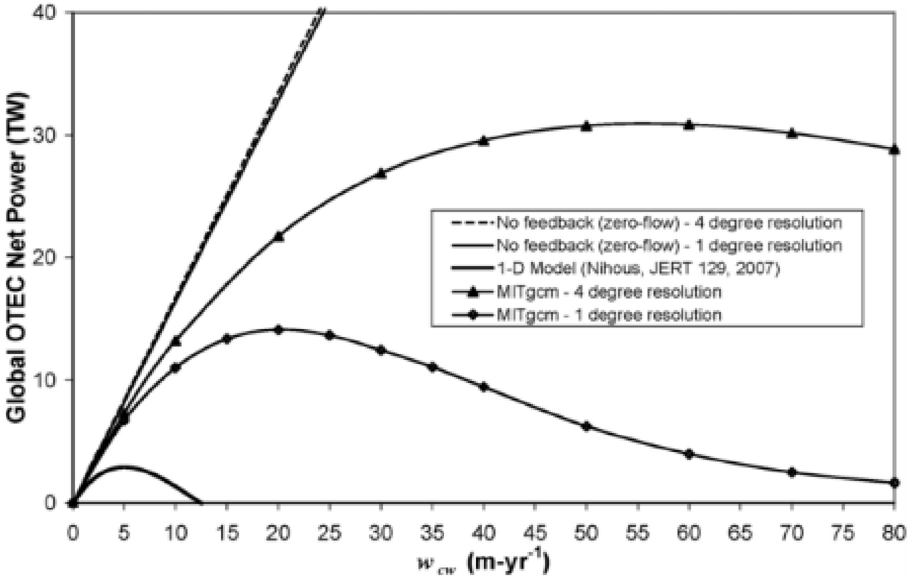
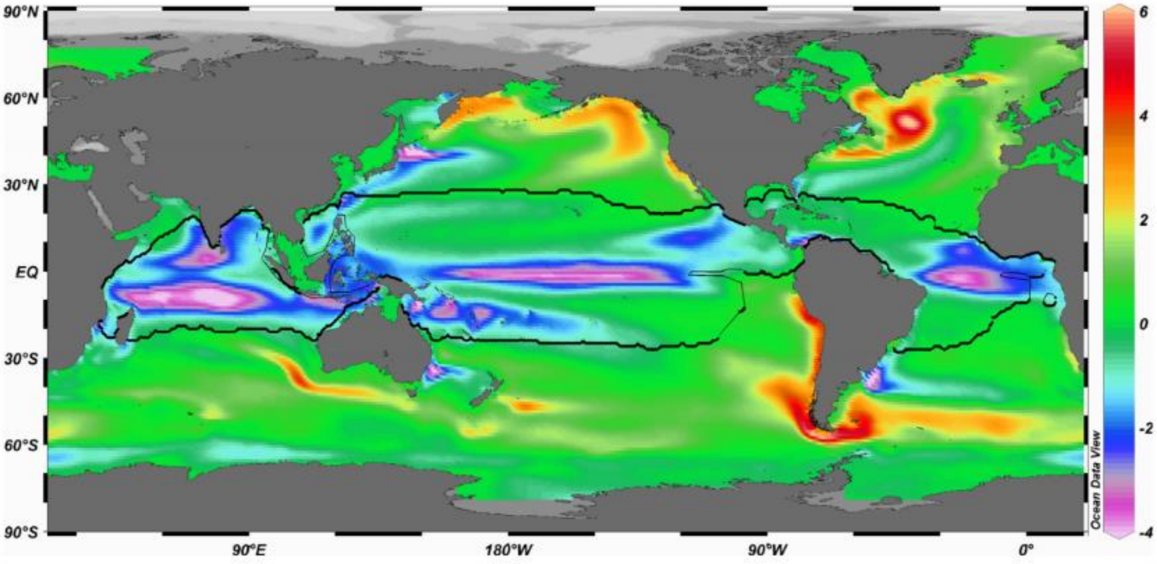


Figure 2.3. Yearly averaged global OTEC power as a function of OTEC flow intensity w_{cw}.

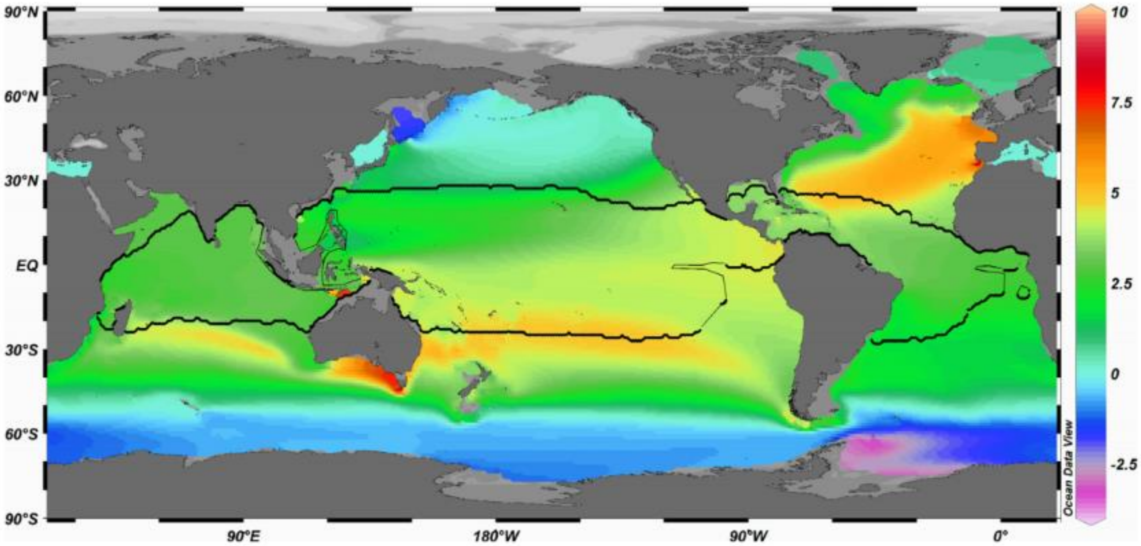
The straight line in Figure 2.3 represents the case if the ocean did not change (meaning the temperature difference between the surface and deep water layers remained the same even after large-scale OTEC was operational). With the improved resolution the OTEC resource maximum has now decreased to about 14TW. This maximum is also achieved at a lower flow rate of 20 m/yr. These conclusions contrast sharply with those from the coarser grid. The revised OTEC power limit is roughly half the previous value, but it is achieved with an OTEC flow intensity only one-third as large. In truth, this does not mean that OTEC systems are predicted to be more "efficient" in higher-resolution simulations; instead, it reflects the fact that in all simulations, OTEC systems experience less adverse seawater temperature feedback at lower values of w_{cw}. The overall OTEC flow rates involved are considerable, and of the same order of magnitude as large components of the global oceanic circulation.

To get a sense of the number of actual OTEC plants that would correspond to a given OTEC flow intensity w_{cw}, the simplest way would be to divide the corresponding zero-feedback power in Figure 2.3 by a nominal plant size (100MW is broadly considered to be a single-unit commercial target given technological limitations on the deep cold seawater pipe size). Since power production with given hardware is dependent on local conditions, however, it would be more consistent to assign the nominal commercial plant a given deep seawater flow rate. One would then multiply w_{cw} by the area of the OTEC region and divide this overall deep seawater intake flow rate by the reference value, such as 300 $\frac{m^3}{s}$per 100MW system (rated at typical, fixed seawater temperatures). For example, with w_{cw} = 20 m/yr when long-term global OTEC power production would peak, the first method would yield 330,000 plants whereas the second would correspond to 240,000 plants. On the average, though, it can be said that if deployed together, those systems would effectively lose about half of their power rating from adverse feedback on the seawater temperature field.

The results from the current 1deg MITgcm model also show lasting OTEC-induced cooling of the surface layer in the OTEC region can be sustained as long as some warming occurs elsewhere, such that the overall heat flux between the ocean and the atmosphere eventually returns to zero. See Figure 2.4.



(a)



(b)

Figure 2.4. OTEC induced temperature changes for a flow velocity of 20 m/yr (maximum global OTEC production). (a) Yearly averaged temperature change (°C) in the surface layers (to 55 m). (b) yearly averaged temperature change (°C) in deep-seawater-intake layer (centered at 1160 m depth).

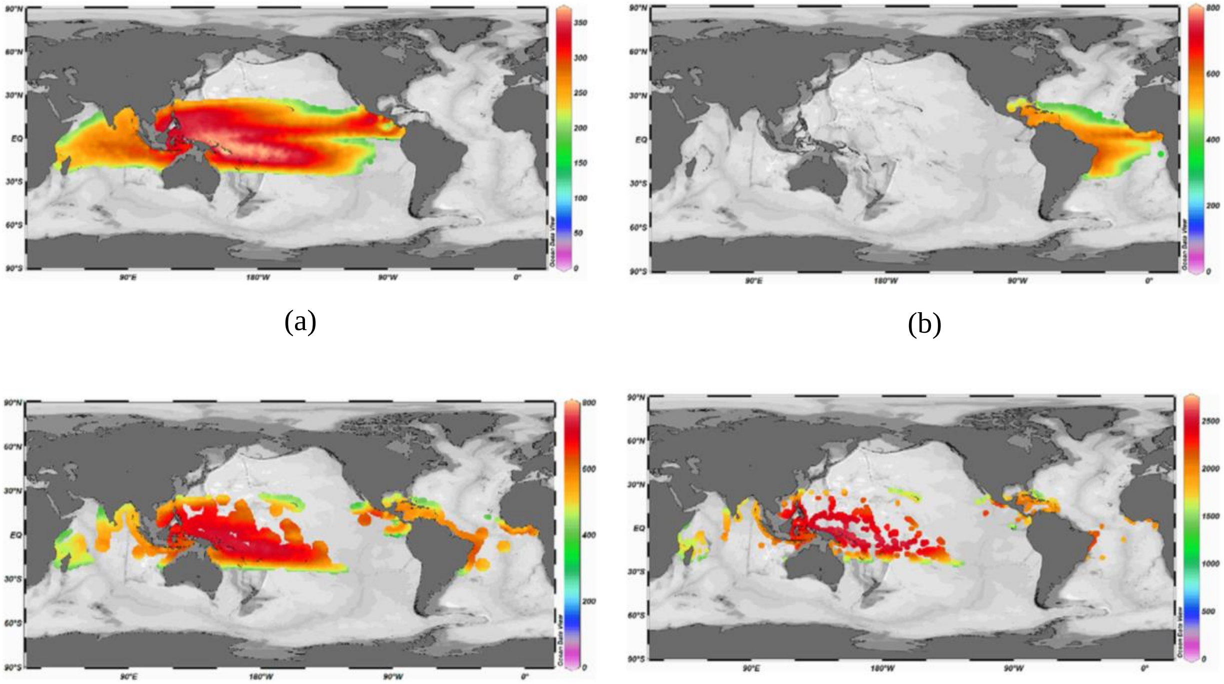
Environmental effects at maximum OTEC power production were qualitatively similar to (example Fig 2.4), but quantitatively more acute than those reported earlier from the 4° grid. A significant boost of the oceanic thermohaline circulation would occur. The refined MITgcm was then utilized to assess OTEC resources under selected ocean regions within the global ocean as described below.

3) Rajagopalan and Nihous (2013c)

In **1)** and **2)**, the OTEC was implemented globally as shown in Figure 2.1. Here, the OTEC implementation is selected based on the temperature difference of 18°C, as well as some geographical constraints. The feasibility of deploying OTEC plants across the global ocean as shown in Figure 2.1 would depend on the in-situ manufacture of a fuel with the extracted energy from plants far from landmasses. While this large-scale scenario may fit well within a future hydrogen economy, a more practical approach would be to limit OTEC deployment in the nearer term to within some distance of land. The selected area may correspond, for example, to the Exclusive Economic Zone (EEZ) of maritime nations, or be defined where large submarine power cables would remain cost effective. The large-scale deployment of OTEC was also shown to have potential environmental effects far from the OTEC region itself, (see for example Figure 2.4), suggesting that valuable information on the system’s response could be garnered by imposing specific geographical constraints on the OTEC domain. Thus, a more practical OTEC development roadmap and uncertainties regarding distant potential environmental effects both provide ample motivation for the work done in this study.

The four regions chosen for this study are shown in Figure 2.5. Two of those correspond to a restriction of the OTEC region on the basis of distance to coastlines. The case labeled "EEZ" excludes areas favorable to OTEC (with 18°C temperature difference) that lie outside of any Exclusive Economic Zone. The export of OTEC electricity using power cables over long distances, even within the EEZ limit of 200 nautical miles, would be costly, however. This motivated a more restrictive simulation labeled "100 km," where OTEC plants would only be deployed within about 100 km of any coastline. Given the 1^o x 1^o horizontal resolution of MITgcm in this study, the corresponding OTEC region is defined by all numerical cells in the OTEC zone that are also adjacent to coastlines. A broad asymmetry of environmental responses in the Indo-Pacific and Atlantic oceans, respectively, was apparent in earlier global OTEC simulations, given in **1)** and **2)**. To further test this point, two scenarios labeled "INDO-PACIFIC" and "ATLANTIC" are also considered. The geographic extent of the corresponding OTEC implementation regions is unambiguously defined since the major oceanic basins are separated by continents within the tropical latitudes of interest.

The results of the study are shown in Figure 2.6. In previous results, OTEC power production was reported as a function of w_{cw}. In this study, the OTEC implementation area is different in each case (Indo-Pacific, … 100km). This necessitates a different metric, the *nominal OTEC net power*, to compare results from these cases. Remarkably, the "EEZ" simulations yielded nearly the same overall OTEC net power maximum as "GLOBAL" (See study # **2)**). Considering a ratio of implementation areas close to two for these scenarios, the average OTEC power density at maximal output is therefore about twice as great in "EEZ" as in "GLOBAL". It also turns out that the maximum output in "EEZ" was achieved at a flow rate intensity of w_{cw} equal to 40 m/yr, or twice the value corresponding to peak power in "GLOBAL." With OTEC operations restricted within 100 km of coastlines, a peak OTEC net power production of 11.9 TW could still be achieved despite an implementation area more than eight times smaller than the entire OTEC region. Here, the average power density does not quite scale with the inverse of the OTEC implementation area. The strong power maximum, though, corresponds to a much greater OTEC seawater flow rate intensity w_{cw}=140 m/yr. When OTEC is only implemented in the Indo-Pacific region, the simulation outcome generally resembles that for "GLOBAL," with a peak power of 11.8 TW roughly scaled down with implementation area, but achieved for the same value w_{cw} = 20 m/yr.



(a) (b)

(c) (d)

Figure 2.5. OTEC implementation under geographical constraints. All plots colored by nominal power density in kW/m^2. (a) Indo pacific (b) Atlantic (c) EEZ (d) 100 km of shoreline.

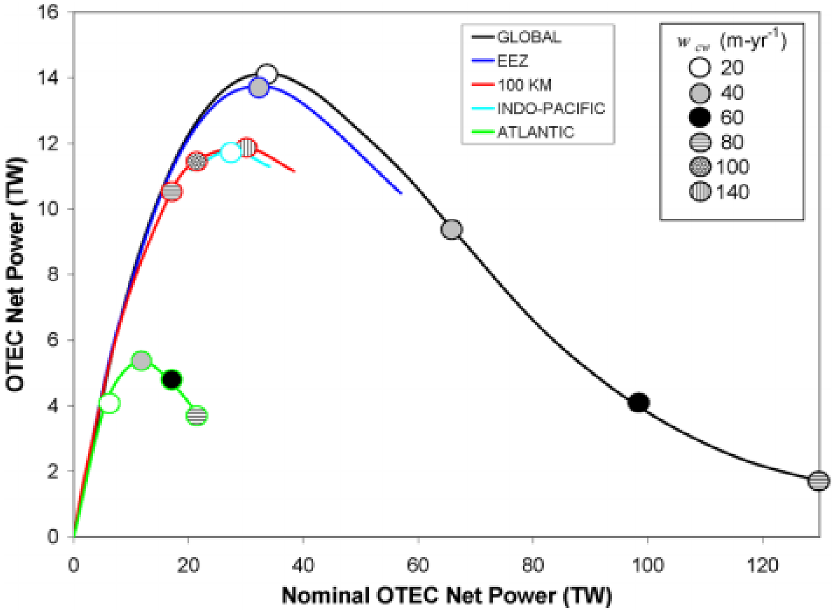


Figure 2.6. Yearly averaged OTEC power: estimate from MITgcm as a function of nominal value.

The behavior of simulations for OTEC in the relatively small Atlantic region seems quite different. This likely stems from a greater sensitivity of the THC to flow perturbations in an ocean that is ventilated at a faster rate. Here, a maximum OTEC power of only 5.4 TW is reached when w_{cw}= 40 m/yr. In each case, it appeared as though producing half the predicted power maximum would substantially limit large-scale environmental temperature changes. The knowledge acquired by modeling OTEC implementation in MITgcm was also leveraged for studying another interesting phenomenon, artificial upwelling. This is briefly explained below.

4) Rajagopalan and Nihous (2014)

Artificial upwelling of nutrient rich deep water into surface layers of oligotrophic ocean can enhance oceanic food webs. Since in an OTEC plant the deep water is brought to the surface and expelled for generation of electric power, the upwelling so generated was considered to be a collateral benefit of OTEC. Later, researchers suggested that upwelling can result in atmospheric carbon sequestration. This would occur if nitrogen-fixing diazotrophs bloomed after most upwelled nutrients (including excess dissolved inorganic carbon) had been consumed by other phytoplankton species (e.g., eukaryotes). However, some researchers argued that diazotroph blooms would be inhibited by the loss of upper water column stratification under widespread upwelling scenarios. This study examined how the properties of the water column, such as stratification, vary with widespread artificial upwelling.

The MITgcm model used in **2) & 3),** with one degree horizontal resolution, was modified to study upwelling. Before the modification, it was determined that the MITgcm model estimates of mixed layer depth agree with published data. Figure 2.7 shows good comparison between published data and MITgcm results for mixed layer depth (MLD). In the MITgcm model, artificial upwelling can be represented by a sink at the depth of water withdrawal coupled with a source of the same strength close to the surface. The region chosen for implementation is the North Pacific Subtropical Gyre (NPSG).

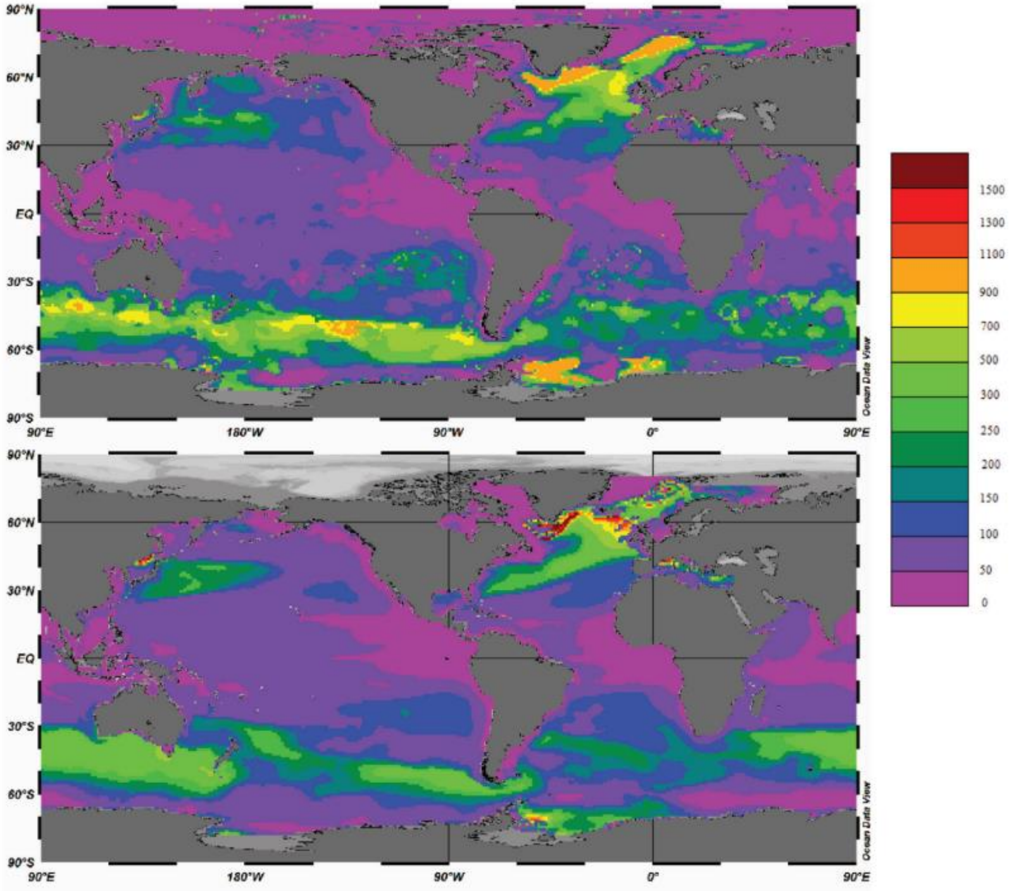
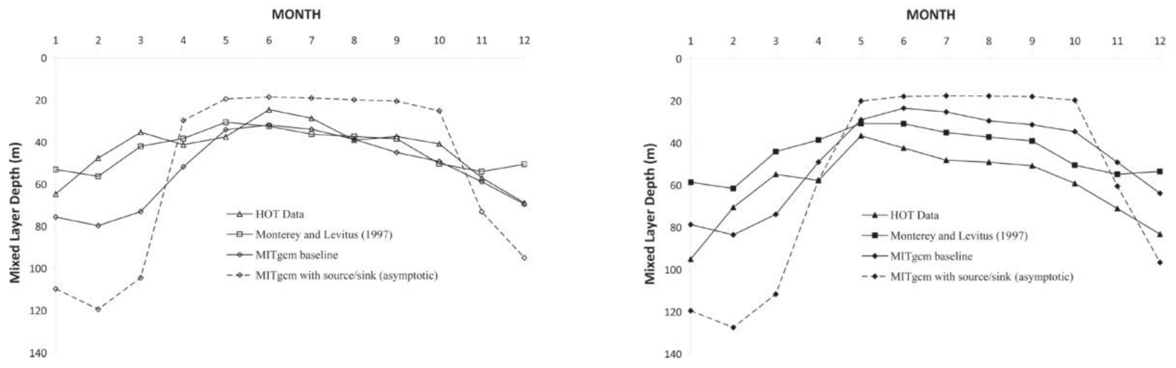


Figure 2.7. Maximum monthly averaged mixed-layer depth (m): top, observations; bottom, MITgcm calculations.

The results of the study are summarized in Figure 2.8. In Figure 2.8(a), MITGcm results, with and without artificial upwelling, is compared with published results from the World Ocean NOAA Atlas (Monterey and Levitus, 1997), and with observations from Station KAHE of the Hawaiian Ocean Time series (HOT). In Figure 2.8(b), the comparison is with Station ALOHA, also of HOT. The conclusion is that during months with normally deeper MLDs, the mixed layer would deepen further; on the contrary, during months with normally shallow MLDs, the mixed layer would get shallower.



(a) (b)

Figure 2.8. Monthly averaged mixed layer depth. (a) Station KAHE. (b) Station ALOHA.

In the MITgcm model used in case studies **(1)** through **(4)**, there was no atmospheric feedback. This deficiency is addressed in the following publication.

(5) Jia, et al (2018)

In case studies **(1)** through **(4)**, the atmosphere is not explicitly modeled. Instead, fluxes between the ocean and the atmosphere are permitted, for example as a result of oceanic perturbations, but atmospheric fields are assumed to be fixed. This drawback is addressed here by incorporating coupling effects between ocean and atmosphere based on a low complexity but numerically efficient approach.

The global OTEC resource, presented earlier in **2)** and **3)**, was then reassessed with the improved model. The MITgcm grid is similar to the one used in **2)** and **3)**, i.e., it has 1-deg horizontal resolution with 23 layers in the vertical direction. In previous cases, **1)** through **3)**,, the local heat flux, Q, entering the ocean from the atmosphere is modeled as, $Q = Q_{obs} + \lambda(T_{obs} - T_0\ \ )$, where Q_{obs} and T_{obs} are climatological observations of heat flux and temperature and T_0 is the ocean surface layer temperature. $\lambda$is the restoring coefficient. We call this formulation of heat flux the Haney method after the researcher who proposed it. In the present work, this formulation for heat flux is modified as shown here,

$$Q = Q_{obs} + \gamma(T_{obs} - T_0\ \ ) \quad - \nabla.\{\mu\nabla(T_{obs} - T_0)\} \text{ Eq. 1}$$

We call the formulation given in Eq.1 the R-W formulation after the researchers Rahmstorf and Willebrand who proposed it. In Eq. 1, the γterm accounts for longwave radiation heat flux to temperature. The last term in Eq. 1 is a diffusive operator and accounts for the horizontal transport of heat flux in the atmosphere. The R-W formulation is further modified to account for grid difference from the grid used in the Rahmstorf and Willebrand original work. We call this the R-Wx40 formulation.

MITgcm model runs were then carried out with the thermal boundary conditions as described above. OTEC implementations considered were “Global”, as in **2)**, and 100km from shoreline, as in **3)**. The main results are summarized in Figure 2.9, below.

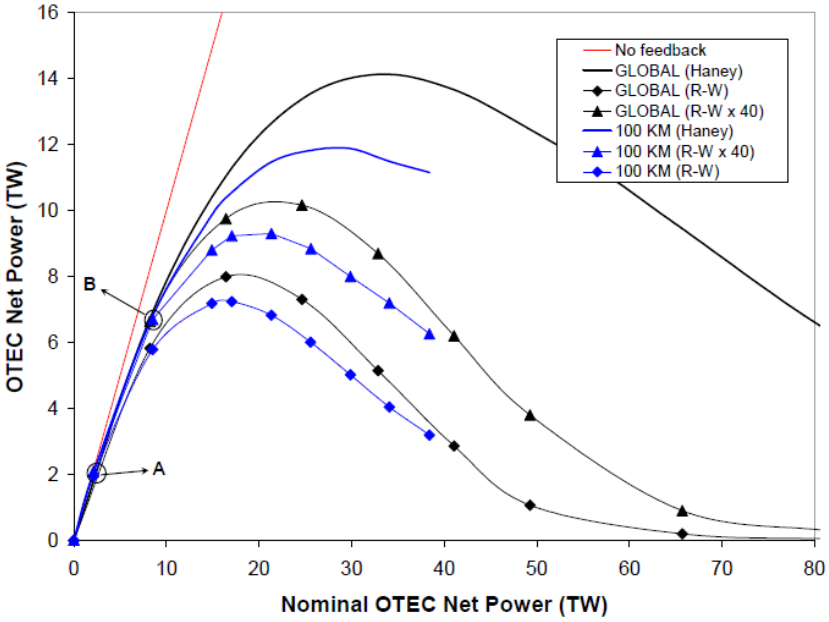


Figure 2.9. OTEC power production as a function of nominal OTEC power for different implementation scenarios and ocean-atmosphere thermal boundary conditions.

The modified boundary condition lowers steady-state OTEC power maxima, 8 to 10.2 TW instead of 14.1 TW for global OTEC scenarios, and 7.2 to 9.3 TW instead of 11.9 TW for OTEC implementation within 100 km of coastlines. The results also show large-scale environmental effects include surface cooling in low latitudes and warming elsewhere, with a net heat intake within the water column.

In addition to these published journal articles, documenting HINMREC-sponsored research examining OTEC potential and impacts worldwide, HINMREC also undertook a systematic analysis of global OTEC resources. Using the temperature difference between water depths of 20m and 1000m (DeltaT), a good indication of available resources across tropical oceans can be obtained. Values of this difference of less than 18°C are generally considered to be economically non-viable for OTEC power generation. The NOAA National Ocean Data Center’s World Ocean Atlas (WOA) database was used to construct the Worldwide OTEC Thermal Resource map, which can be accessed at this link:

http://www.hnei.hawaii.edu/hinmrec/projects/#world-wide-otec-thermal-resource

and scroll to TemperatureDifferentialWOA2005. This shows the annual and monthly averages of the temperature difference between near-surface and 1000m across the world’s oceans on a quarter-degree horizontal grid. A representative plot, showing DeltaT in the month of February, is shown in Figure 2.10 below. The user can choose any region of interest defined by specific latitude and longitude ranges to view color-coded data of the annual average temperature difference as a function of latitude and longitude. Further, clicking on any location gives a plot of monthly averages of the temperature difference at that point, an example of which is shown in Figure 2.11.

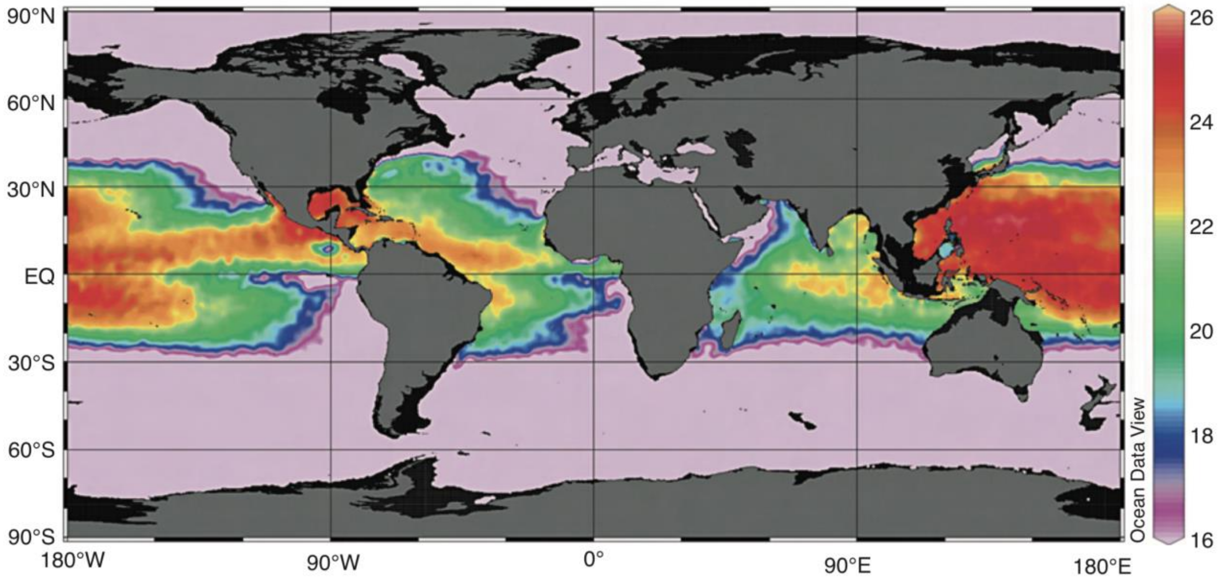


Figure 2.10. OTEC Thermal Resource (DeltaT in degrees F between 20m and 1000m depth) for the month of February, from the TemperatureDifferentialWOA2005 database.

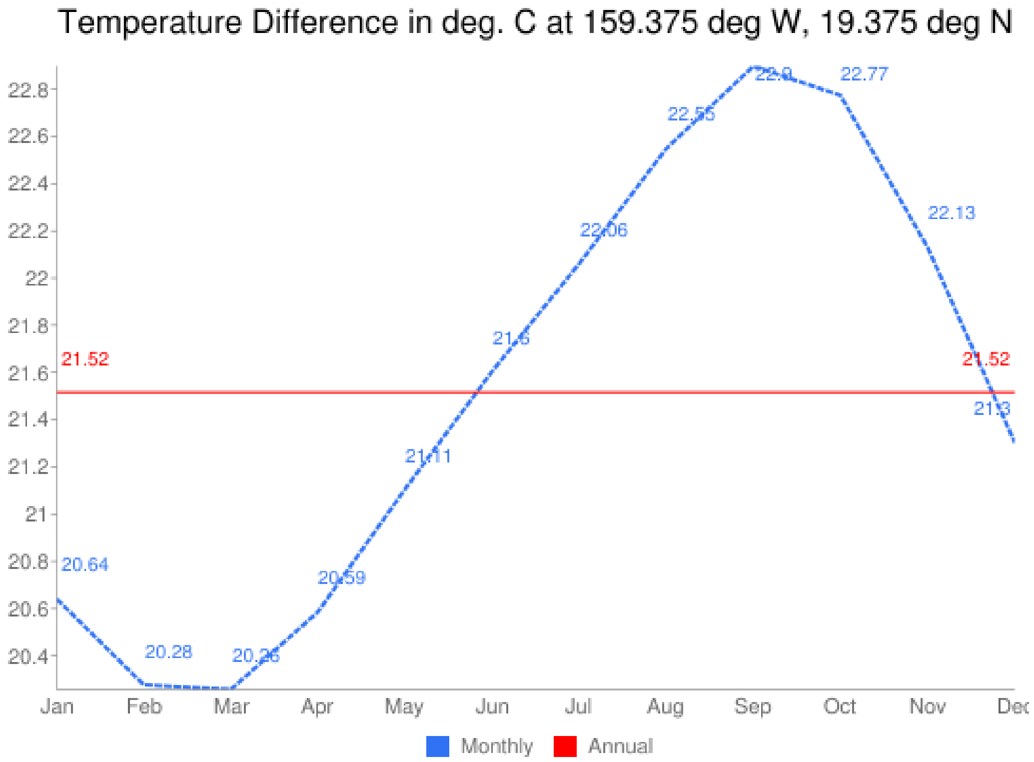


Figure 2.11. Representative annual plot of monthly mean temperature difference obtained from the OTEC TemperatureDifferentialWOA2005 database.

An estimate of OTEC power production capabilities can be made with the temperature difference data. Annual and monthly averages of the power that would be produced by a single generic OTEC plant rated at 100 MW in standard conditions is available at the link, http://www.hnei.hawaii.edu/hinmrec/projects/#world-wide-otec-thermal-resource, and scroll to PowerMaps. The display is limited to a latitude band between 30°S and 30°N. The link provides the user with a color-coded distribution of OTEC power production from the generic 100 MW plant, in GWh per year. The user can choose any region of interest between 30°S and 30°N to view detailed values of annual average power. Further, clicking on any location provides the user with a plot of the monthly averages of net power at that spot, in GWh per month. Representative plots of each are shown in Figures 2.12 and 2.13. Further information is found in "Ocean Thermal Energy Conversion" listed under Reports and Publications below.

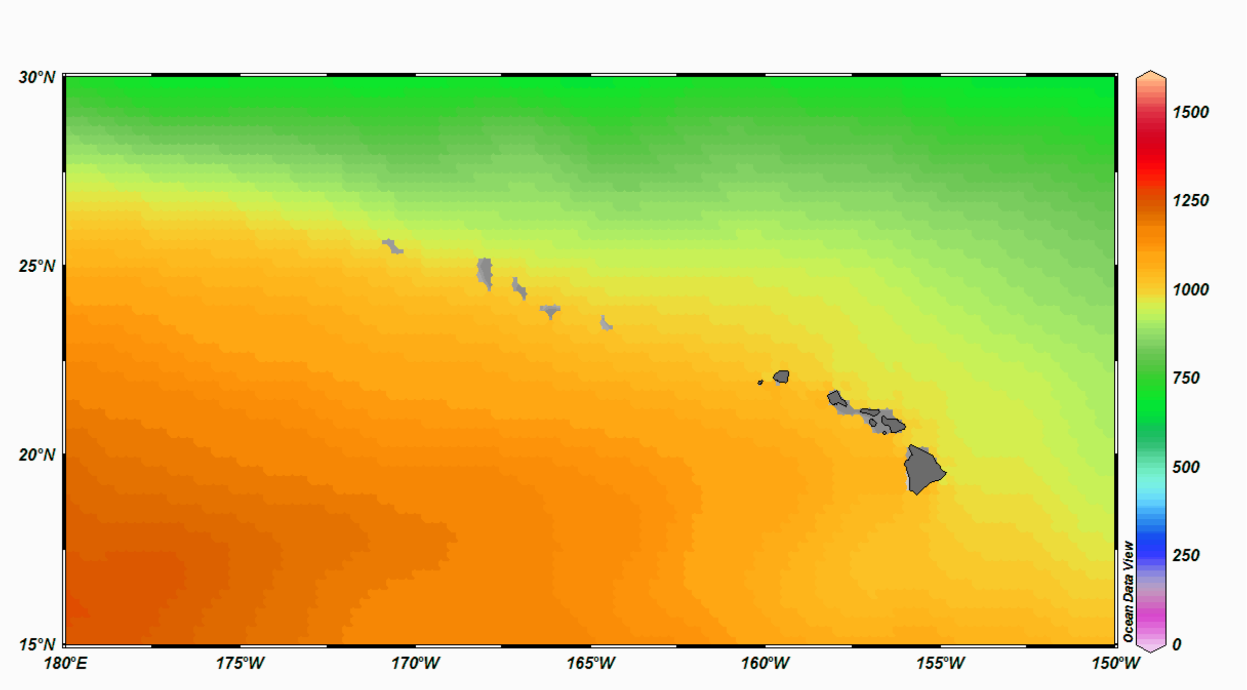


Figure 2.12. Annual average power in GWh/year near Hawaii, from HINMREC-developed PowerMaps website.

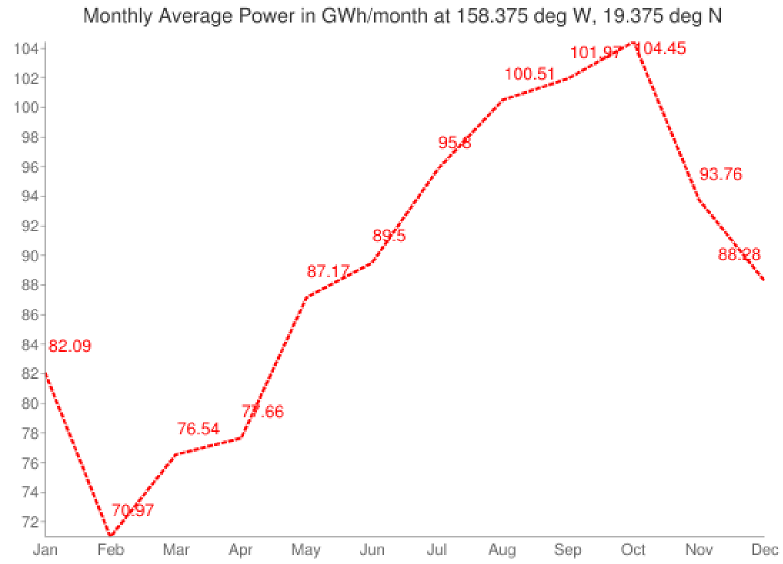


Figure 2.13. Monthly average power in GWh, from a location near Hawaii.

An OTEC discharge water model was implemented leading to the protocol for environmental monitoring parameters (nutrients & biological; CTD; and carbonate cycle). This HNEI protocol has been adopted by UH for ongoing Honolulu SWAC baseline measurements (ONR funding).

Reports and Publications

Book Chapters

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Vega, L.A., February 2016. Ocean Thermal Energy Conversion, Renewable Energy Systems, Springer, New York, NY, https://doi.org/10.1007/978-1-4614-5820-3_695.

Journal Publications

Nihous, G.C., 2011, A Discussion of Endoreversible Engines at Maximum Output, Fundamental Journal of Thermal Science and Engineering, Volume 1, Issue 2, 73-8, http://www.frdint.com/.

Rajagopalan, K., Nihous, G. C. 2013a. Estimates of global Ocean Thermal Energy Conversion (OTEC) resources using an ocean general circulation model. Renewable Energy, 50, 532-540.

Rajagopalan, K., Nihous, G. C. 2013b. An assessment of global ocean thermal energy conversion resources with a high-resolution ocean general circulation model. Journal of Energy Resources Technology, 135, 4.

Rajagopalan, K., Nihous, G. C. 2013c. An assessment of global Ocean Thermal Energy Conversion resources under broad geographical constraints. Journal of Renewable and Sustainable Energy, 5, 6, doi.org/10.1063/1.4850521.

Rajagopalan, K., Nihous, G. C. 2014. Predictions of Water-Column Properties under Widespread Artificial Upwelling Scenarios in the North Pacific Subtropical Gyre using an Ocean General Circulation Model. Journal of Marine Environmental Engineering, 9, 4.

Jia, Y., Nihous, G. C. and Rajagopalan, K. 2018. An Evaluation of the Large-Scale Implementation of Ocean Thermal Energy Conversion (OTEC) Using an Ocean General Circulation Model with Low-Complexity Atmospheric Feedback Effects. Journal of Marine Science and Engineering, 6, 12.

Nihous, G.C., March 2018, A Preliminary Investigation of the Effect of Ocean Thermal Energy Conversion (OTEC) Effluent Discharge Options on Global OTEC Resources, Journal of Marine Science and Engineering, 6, 25; doi:10.3390/jmse6010025.

Conference Presentations and Proceedings

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Comfort, C. M., Vega, L., September 2011. Environmental Assessment of Ocean Thermal Energy Conversion in Hawaii: Available data and a protocol for baseline monitoring, OCEANS'11 MTS/IEEE, Waikoloa, Hawaii. doi:10.23919/OCEANS.2011.6107210.

Vega, L.A., DeVisser, A., Cable, B., June 2013. Wave Energy Test Site (WETS): Marine Corps Base Hawaii (MCBH), Energy Ocean International, Warwick, RI.

Vega, L.A., June 2013. Wave Energy and Ocean-Thermal Energy: Resource Assessment and Modeling, Energy Ocean International, Warwick, RI.

Vega, L.A., April 2014. Ocean Thermal Energy Conversion, Global Marine Renewable Energy Conference (GMREC, in conjunction with METS 2014), Seattle, WA.

Vega, L.A., June 2014. Ocean Thermal Energy Conversion (OTEC), International Offshore and Polar Engineering Conference, Busan, Korea (invited by organizers).

Vega, L.A., September 2015. OTEC: Past, Present & Future 3rd OTEC Symposium, (keynote speaker), 3rd International OTEC Symposium 2015, Kuala Lumpur, Malaysia.

Vega, L.A., February 2016. Ocean Thermal Energy Conversion (OTEC), Ocean Energy Europe 2016, Brussels, Belgium, (poster).

TASK 3: WAVE RESOURCE MODEL, WAVE FIELD MEASUREMENTS AND DATA ANALYSIS

This task began with development of a numerical wave model system to provide an operational wave forecast and long-term hindcast. The forecast dataset aids in the installation, maintenance, and retrieval of WEC devices at the site and assists in evaluation of WEC device performance. The long-term hindcast provides a basis for wave energy resource characterization and assessment around the main Hawaiian Islands, identification of the most favorable conditions for operation of wave power systems, as well as an analysis of the extreme wave conditions at WETS. New datasets and improved model schemes have been utilized for the upkeep of the numerical model system.

3.1 Wave Forecasting

Hawaii has a complex wave climate related to its location in the mid-Pacific location and the substantial effects of the archipelago. The main wave regimes in Hawaii are shown in Figure 3.1. The persistent trade winds generate waves from the northeast to east throughout the year. Extratropical storms near the Kuril and Aleutian Islands generate swells toward Hawaii from the northwest to north in winter. The south facing shores experience moderate swells from the year-round Southern Hemisphere Westerlies that are augmented by mid-latitude cyclones in summer. Tropical and subtropical storms and passing cold fronts can generate waves from all directions. Initial work to develop the WEC test site at MCBH involved researching wave energy resource information required to select coastal segments for specific WEC technology, and to initiate engineering design incorporating production estimates and the wave loading that devices must survive during their life cycle. As the design progressed beyond the preliminary stages, site specific wave forecasting and resource assessment were required and led to further research efforts.

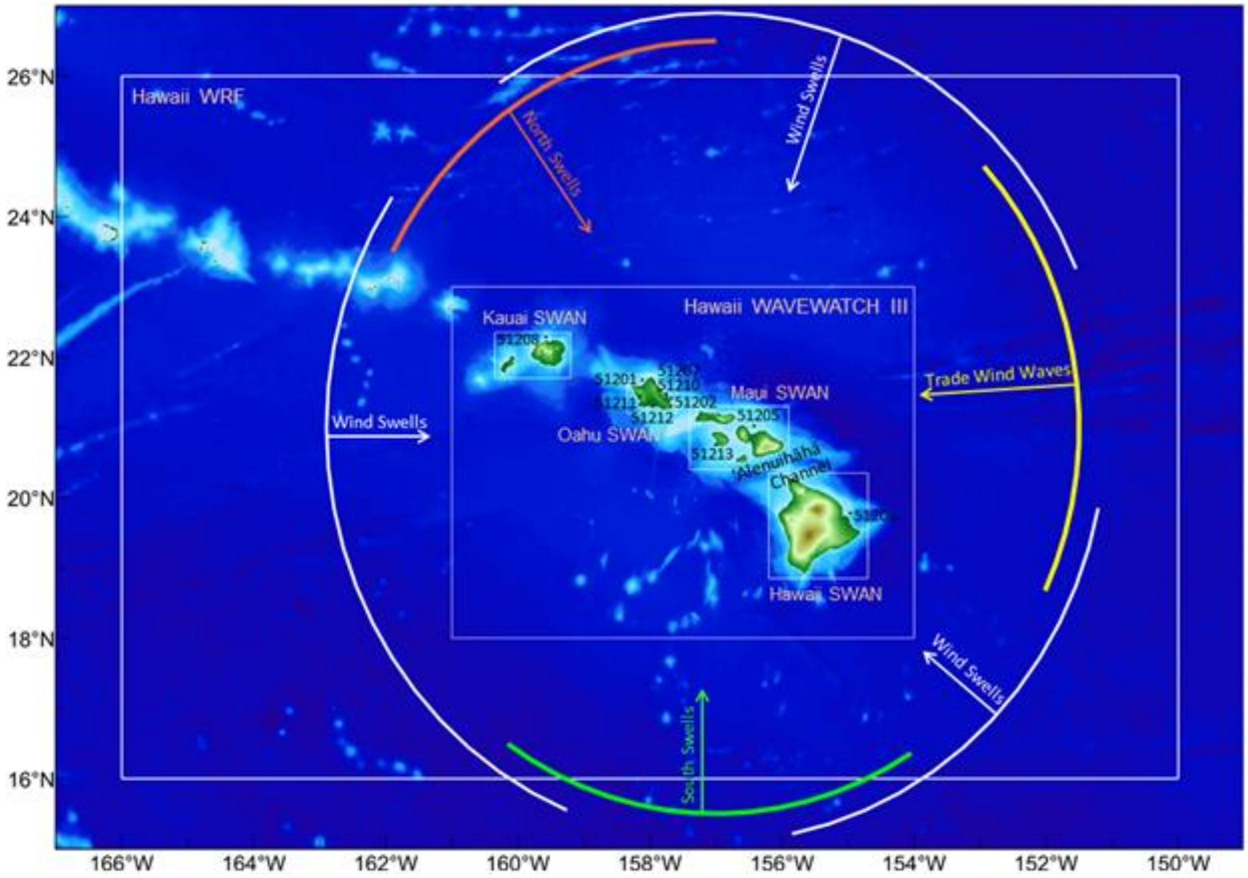


Figure 3.1. Nested computational grids, location map, and illustration of wave climate.

Faculty from the Departments of Ocean and Resources Engineering (ORE) and Oceanography (OCE) at UH led the initial work. ORE assembled a numerical wave model system with the third-generation spectral wave models WAVEWATCH III and Simulation WAve Nearshore (SWAN) based on a suite of nested grids from globe to the Hawaiian Islands. WAVEWATCH III, despite being developed for open oceans and shelf seas, can depict shadowing of the wave field by the islands and heightened seas with small fetches in interisland channels and around headlands. SWAN is better suited for nearshore environments due to its efficient implicit scheme to compute wave processes in fine resolution and ability to account for triad wave interactions in shallow water. ORE researchers also conducted additional parameterizations for energy dissipation due to wave breaking and bottom friction in the tropical fringing reef environment.

High-quality global and regional wind data are crucial for numerical wave models to capture the complex wave conditions in Hawaii. The NOAA NCEP Global Forecast System (GFS) provides a 7.5-day wind forecast at 0.5° resolution four times daily, while the more comprehensive Climate Forecast System Reanalysis (CFSR) produces assimilated surface winds for the entire globe at 0.5° resolution from 1979 to 2011 and 0.205° afterward. Those global forecast and reanalysis datasets can resolve the synoptic weather conditions very well, and provide boundary conditions for downscaling of regional atmospheric models. The UH Department of Atmospheric Sciences downscales the global GFS and CFSR datasets with the MM5/WRF (Fifth-Generation Penn State/NCAR Mesoscale/Weather Research and Forecasting) models to provide the high-resolution surface winds in Hawaii. The MM5/WRF model covers the entire State of Hawaii with a 6km resolution (http://www.soest.hawaii.edu/MET/Faculty/wrf/arw/). With proper depiction of terrain and land surface conditions and assimilation of the satellite observation, the MM5/WRF model can resolve the modification of large-scale wind flows by islands with mountain heights ranging from 500 to 4100m to account for the orographic and land-surface effects in Hawaii. The high-resolution regional wind data complements the global datasets (GFS/CFSR), providing a complete description of synoptic and mesoscale weather systems in distant and local areas. The complete datasets allow the wave model system to resolve distant swells as well as local contributions to the wind waves.

ORE implemented the numerical model system with wind forcing from GFS and regional MM5/WRF model to produce a wave forecast in the Hawaiian Islands at 6km resolution and around individual major islands at 600m resolution. The forecast is updated once per day, and the output includes hourly significant wave height, peak period, and peak direction at each computational grid as well as the partitioned wave parameters and 2D spectra at predefined locations over the 7 day forecast horizon. For quality control, the daily forecasts are compared with real-time measurements from 10 nearshore and offshore buoys in Hawaii. Table 3.1 shows the performance indicators of wave forecast at WETS. The results for the first three days are quite consistent with a root mean square error less than 0.26 m, correlation coefficient above 0.90 and scatter index less than 15%. The model performance starts deteriorating after the fourth day reflecting the uncertainty in the weather forecast, yet still provides a reasonable description of the wave conditions. The daily 7-day wave forecast complements buoy measurements for supporting at-sea operation planning and day-to-day operation of WEC devices.

The wave forecast continues to be updated daily under Navy funding. Regular improvements to the model are now fully funded under the Navy. The operational wave forecast and its validation with real-time measurements from the WETS buoys (CDIP #198 and CDIP #225) are displayed at the UH Pacific Islands Ocean Observing System (PacIOOS) web pages:

http://www.pacioos.hawaii.edu/waves/buoy-kaneohe/#forecast, and

http://www.pacioos.hawaii.edu/waves/buoy-kaneohe-wets/#forecast.

Table 3.1. Performance indicators of wave forecasts at WETS

	Day						
Significant Wave Height	1	2	3	4	5	6	7
90% error bound (±m)	0.37	0.37	0.39	0.43	0.50	0.56	0.62
Scatter index (%)	12.5	12.5	13.7	15.7	18.9	22.4	23.9
RMS Error (m)	0.24	0. 24	0.26	0.29	0.35	0.41	0.44
Regression Slope	0.86	0.88	0.87	0.85	0.83	0.77	0.73
Correlation Coefficient	0.94	0.94	0.93	0.90	0.86	0.81	0.78

The same wave model system was also implemented for wave hindcasting from 1979 to 2018 with wind forcing from CFSR for the entire globe and downscaled WRF around Hawaii. The 38 years of hindcast includes significant wave heights, peak wave periods, and peak directions of the full and partitioned spectra at each grid point in hourly intervals as well as two-dimensional wave spectra at buoy locations. Energy resource parameters such as wave power and energy period are computed from the hindcast spectrum at selected locations. A thorough validation of the hindcast dataset was conducted with available measurements from 16 offshore and nearshore buoys along the Hawaiian Islands from 1981 to 2018 and altimeters on multiple platforms between 1991 and 2009. Figure 3.2 illustrates, as an example, the comparison of hindcast and measured wave parameters at WETS in 2016. The hindcast captures the year-round wind waves and episodic wind swells as well as the winter north swells across a wide range of wave heights and periods. Despite underestimation at the peak of large swell events due to the low-resolution global winds, the hindcast wave height at WETS has a small mean error of -0.04 m in comparison with the measurements, indicating good model performance. The high-quality hindcast provides a wealth of information for characterization of wave resources and identification of extreme waves in support of WEC development. The long-term dataset exhibits seasonal and interannual variability of wave conditions at WETS as shown in the upper percentile (95th), median (50th), and lower bound (5th) of significant wave height, wave power and energy period distribution in Figures 3.3 and 3.4. The site is sheltered from the low energy south swells and the more extreme northwest swells, is exposed to trade wind waves throughout the year and north swells in the winter months. The persistent waves and multi-modal sea states provide a favorable environment for WEC device testing. Numerical wave modeling has proven to be an important aspect of HNEI's support to the operation of the Navy's wave energy test site.

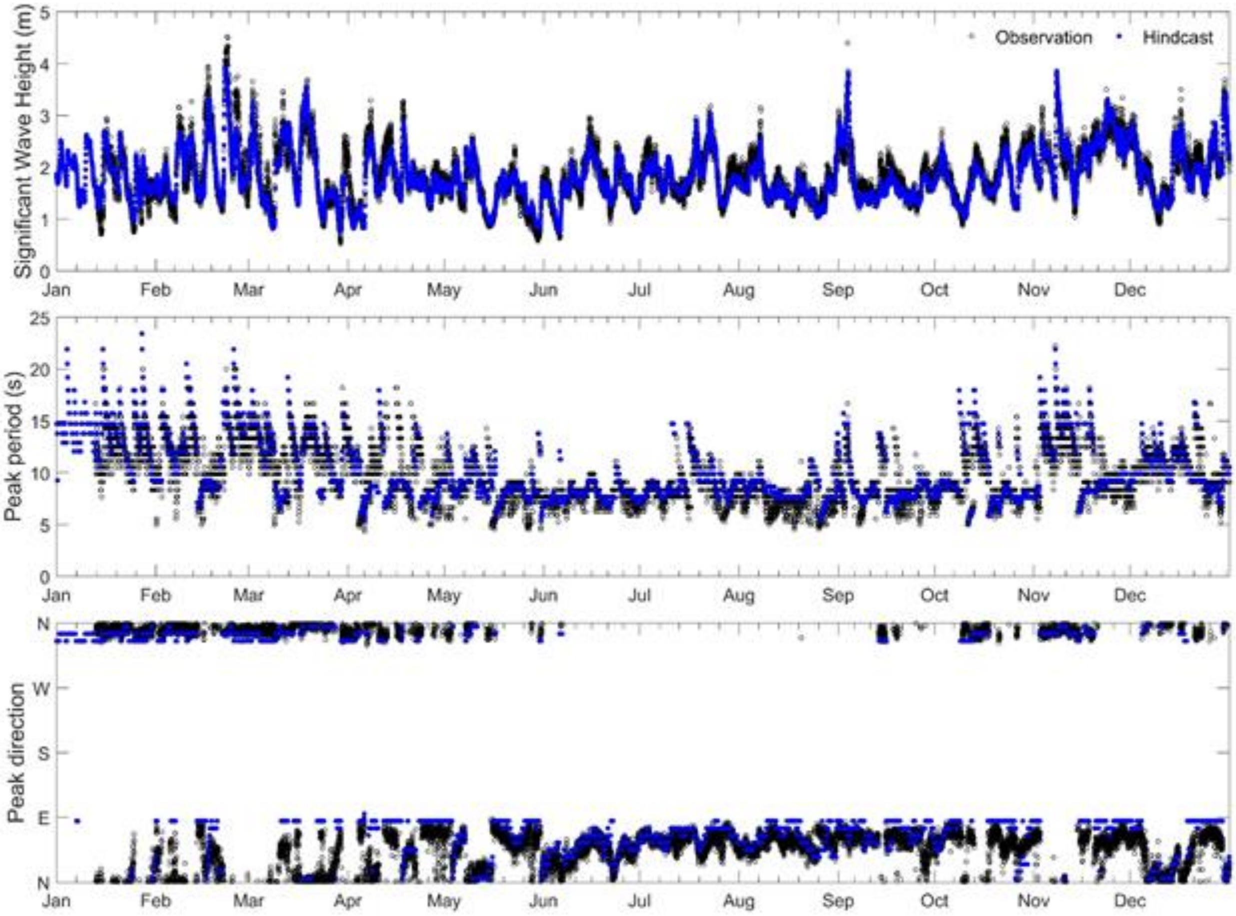


Figure 3.2. Comparison of hindcast and measured significant wave heights, peak periods, and peak directions at WETS in 2016.

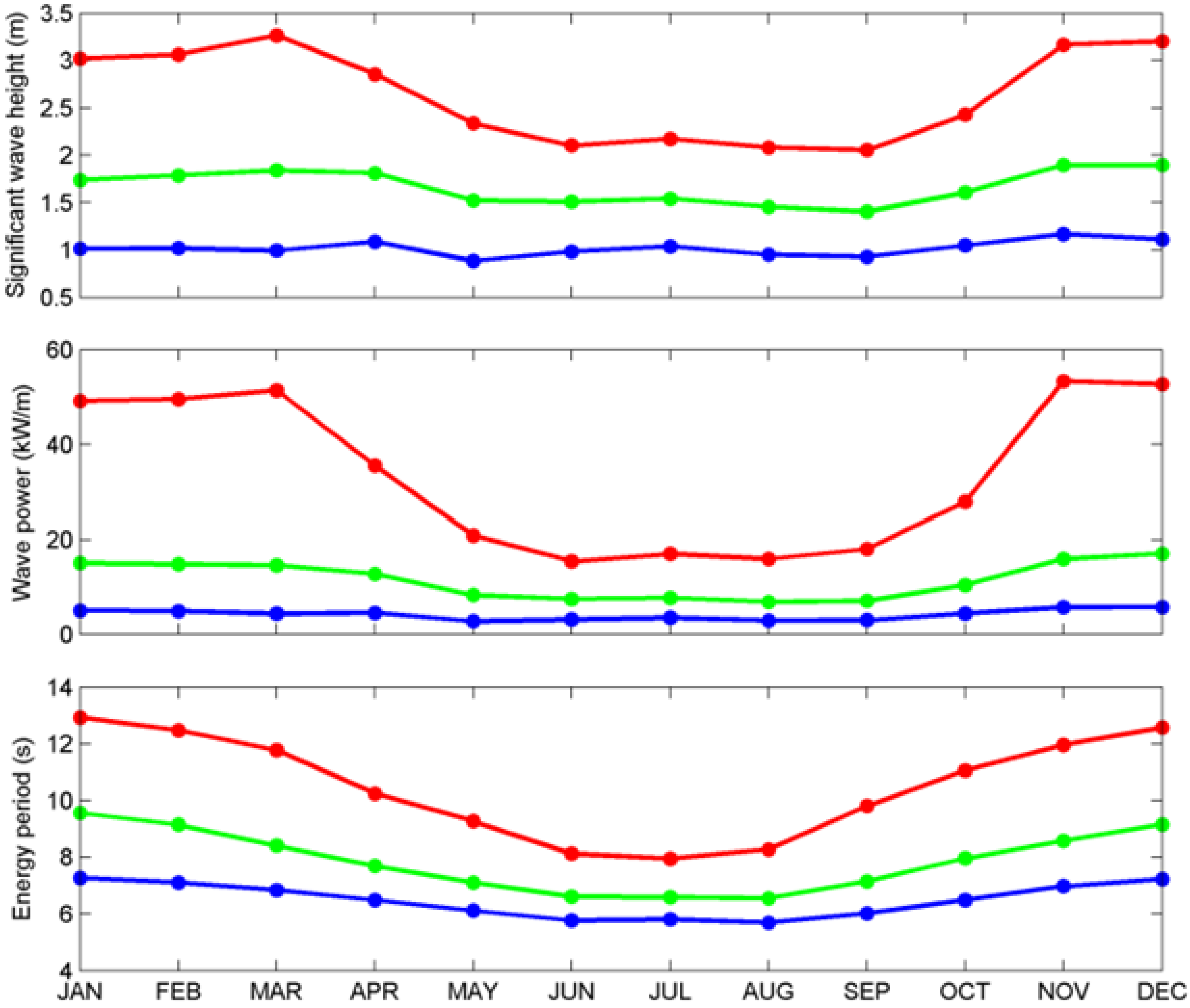


Figure 3.3. Monthly 5th (blue), 50th (green), and 95th (red) percentile significant wave height, wave power and energy period at WETS from the 1979-2017 hindcast.

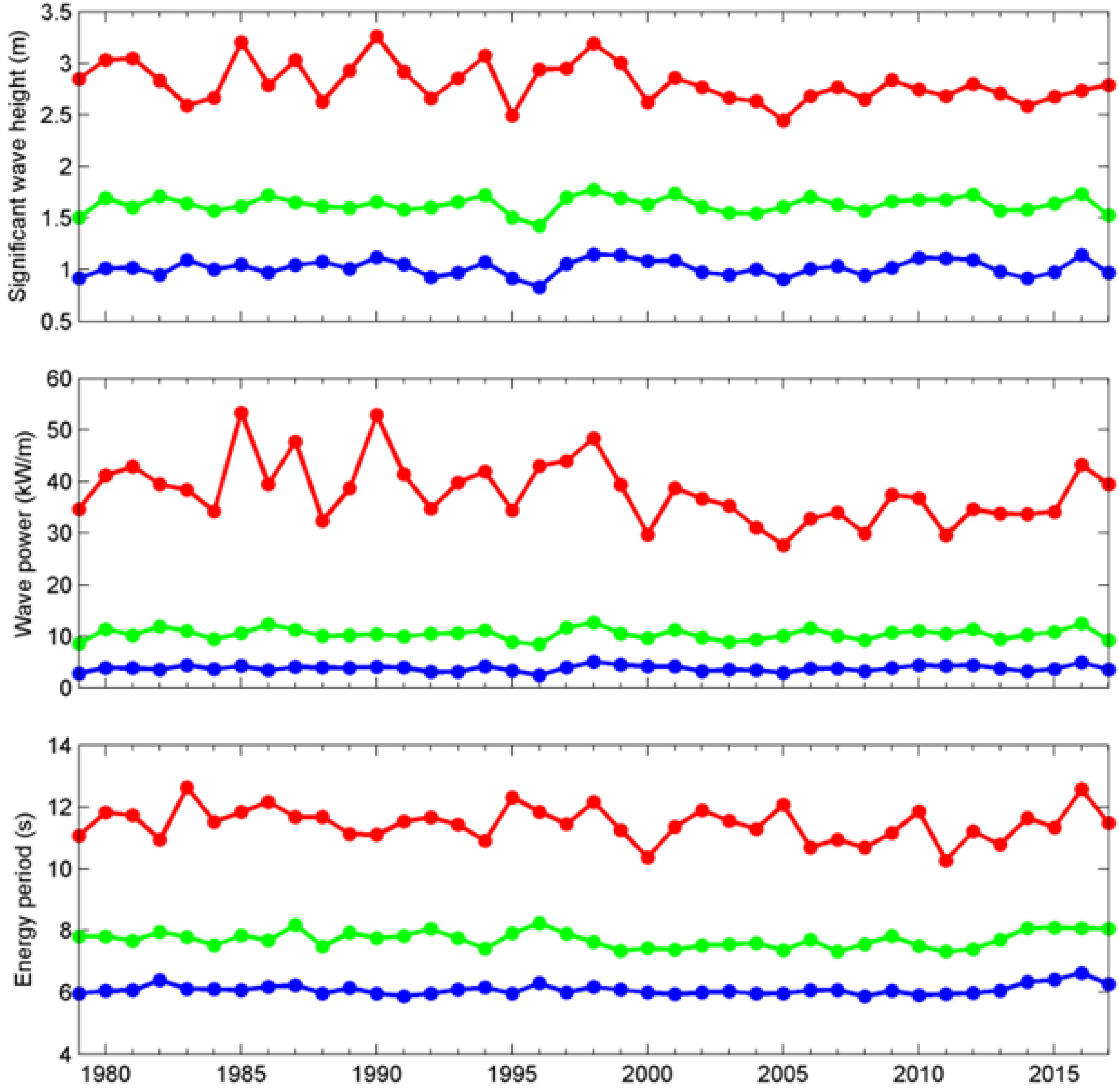


Figure 3.4. The annual 5th (blue), 50th (green), and 95th (red) percentile significant wave height, wave power, and energy period at WETS from the 1979-2017 hindcast.

Under Navy funding, the HINMREC wave hindcast model was upgraded to include extreme wave analysis. For example, NAVFAC funded analysis of wave conditions during hurricanes in the vicinity of WETS, based on hurricane scenarios from downscaling simulations of a global climate model to produce a range of severe wave conditions at WETS. The computed wave height presented as a function of annual exceedance probability enables a risk-based survival analysis of WECs. This study provided a proof-of-concept of the probabilistic approach and a baseline for analysis of hurricane wave conditions under the present and future climate projections, and was presented at the METS2017 conference, “Probabilistic wave parameters for WEC survival analysis at US Navy's wave energy test site in Hawaii”.

For more detail on this and the rest of this work, see the Reports and Publications listed below, (and also related work under subtasks 3.2).

Reports and Publications

Technical Reports

Vega, L., October 2010. Wave Energy Resources for Representative Sites Around the Hawaiian Islands.

Li, N., Stopa, J., December 2012. Wave Power Analysis for Makapuu Point, Oahu.

Li, N., and Cheung, K.F., January 2014, Progress Report: Comparison of Wave Hindcast Model Results with Waverider Measurements: November 2012 - October 2013.

Journal Publications

Stopa, J.E., Cheung, K.F., and Chen, Y.-L. 2011. Assessment of wave energy resources in Hawaii, Renewable Energy Journal, 36, 554-567, doi:10.1016/j.renene.2010.07.014.

Arinaga, R. A., Cheung, K. F. 2012. Atlas of global wave energy from 10 years of reanalysis and hindcast data, Renewable Energy Journal, 39, 49-64. doi:10.1016/j.renene.2011.06.039.

Stopa, J.E., Filipot, J.-F., Li, N., Cheung, K.F., Chen, Y.-L., Vega, L. 2012. Wave energy resources along the Hawaiian Island chain, Renewable Energy Journal, 55, 305-321, doi.org/10.1016/j.renene.2012.12.030.

Stopa, J. E., Cheung, K. F., 2014, Intercomparison of wind and wave data from the ECMWF Reanalysis Interim and the NCEP Climate Forecast System Reanalysis, Ocean Modelling 75, 65–83, doi.org/10.1016/j.ocemod.2013.12.006.

Stopa, J. E., Cheung, K. F., 2014, Periodicity and patterns of ocean wind and wave climate, Journal of Geophysical Research: Oceans, 19, 5563–5584, doi:10.1002/ 2013JC009729.

Conference Proceedings

Li, N., Cheung, K.F., Cross, P., and Vega, L., 2016. Wave energy resource characterization at the US Navy's Wave Energy Test Site, Hawaii, proceedings of the 4th Annual Marine Energy Technology Symposium, Washington DC.

Li, N., Cheung, K.F., Cross, P., and Vega, L., 2017. Probabilistic wave parameters for WEC survival analysis at US Navy's Wave Energy Test Site in Hawaii, proceedings of the 5th Marine Energy Technology Symposium, Washington DC.

Other Presentations

Stopa, J.E., April 2013, Forecasting and Hindcasting Wind Driven Wave Environments, Society of Naval Architects and Marine Engineers (SNAME) Spring 2013 Meeting.

3.2 WETS Wave Measurements and Operational Wave Analysis

This task was necessary to calibrate models and have real time data available during actual testing and operations at WETS.

Prior to HINMREC, a directional Waverider© buoy was located at 100m depth 10 km southeast of WETS at Mokapu. The 9 years of data gathered from 2003 to 2012 was used to calibrate the UH model to ensure that the model correctly captures the diffraction and refraction of the north swells around Kahuku Point (the northern tip of Oahu) before reaching WETS, off Kaneohe.

A directional Datawell Waverider© buoy (CDIP #198) was purchased by HINMREC and installed along the ~80m contour, at a location that would later be very close to the center of WETS and the 60m test berth, in October 2012 (Figure 3.5). This buoy provides real time incoming wave data for use in the evaluation of WEC device performance (see Task 5). Permits were obtained from the US Army Corps of Engineers, US Coast Guard, and State agencies to install the buoy at WETS.

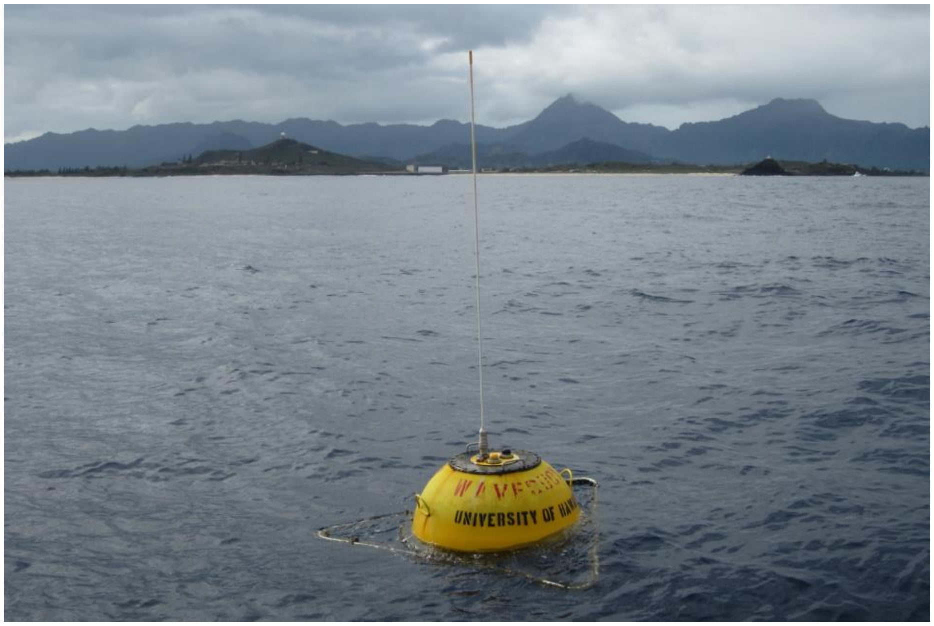
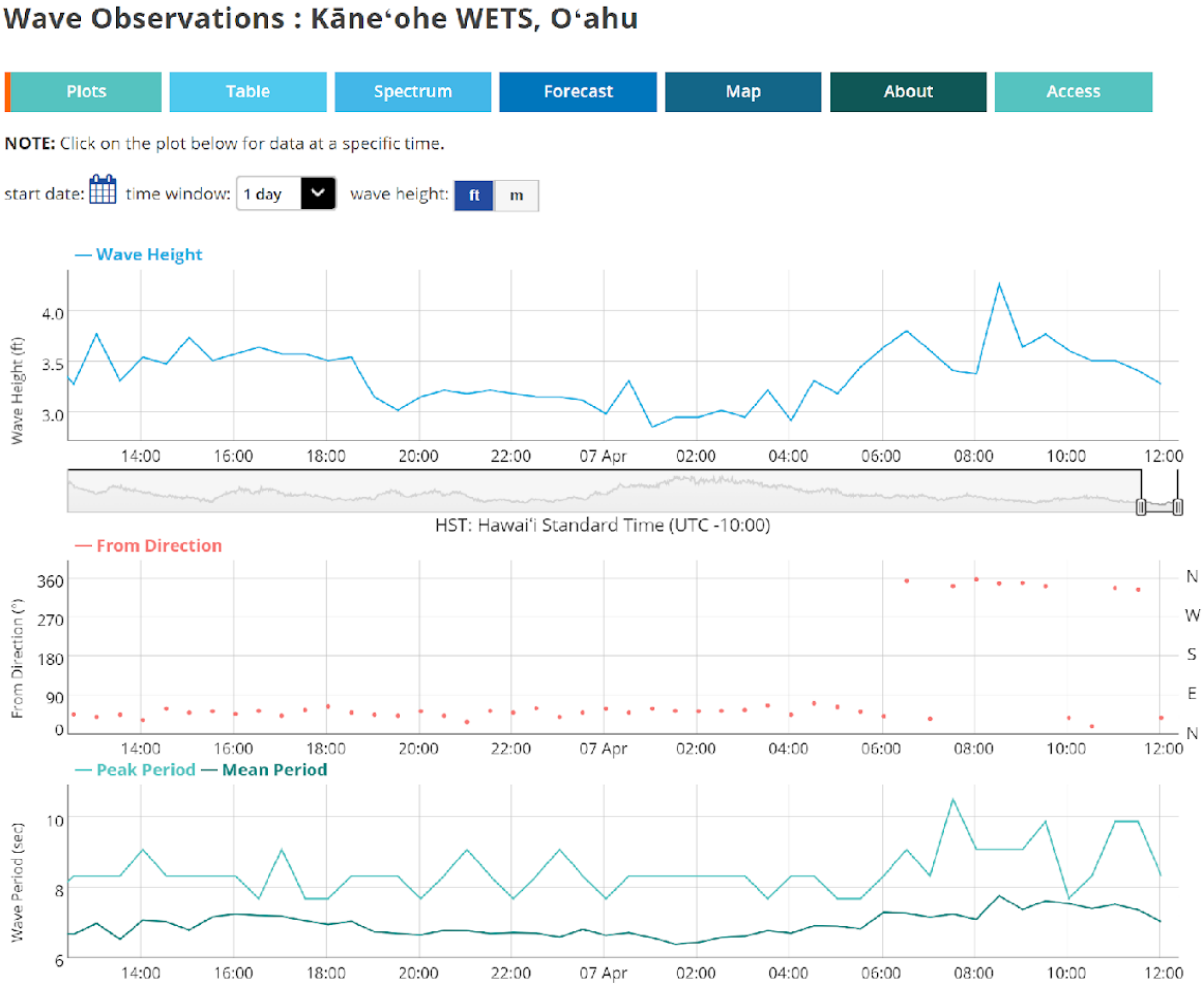


Figure 3.5. Waverider© buoy deployed at WETS, near the 60m test berth.

An additional Waverider© buoy was later purchased under separate funding from ONR, to provide the required measurement redundancy, (CDIP#225). This buoy was installed during August 2016, also along the 80m contour 350 m west of the original. The data from both buoys are used to calibrate the UH high resolution wave model. In addition, the raw data were available to the developers and used by HINMREC in assessing WEC device performance, as described under Task 5. Both buoys will remain deployed at WETS with additional funding from Navy and NOAA to ensure that wave data are available to provide that critical input to the development of power matrices for deployed WECs under test.

Waverider© data, parameters derived from the recorded sea surface elevation time series, is displayed at the UH Pacific Islands Ocean Observing System (PacIOOS) web page http://oos.soest.hawaii.edu/pacioos/, (Figure 3.6), and is also available at the Coastal Data Information Program (CDIP) webpage (http://cdip.ucsd.edu/, CDIP#198 and #225), following standard National Data Buoy Center formats.



Wave Observations : Kāneʻohe WETS, Oʻahu

NOTE: Click on the plot below for data at a specific time.

start date: time window: 1 day wave height: ft m

Figure 3.6. Screen shot of wave data available online http://www.pacioos.hawaii.edu/waves/buoy-kaneohe-wets/.

Intermittent deployments of acoustic Doppler current profilers, which can also measure wave conditions when up-looking, have also occurred under HINMREC funding over the years. (For more detail see the Reports and Publications listed below, and also related work under subtasks 3.1 and 4.3).

Reports and Publications

Technical Reports

Li, N., and Cheung, K.F., 2014. Wave energy resource characterization at the US Navy Wave Energy Test Site and Other Locations in Hawaii. Report submitted to National Marine Renewable Energy Center, Honolulu, Hawaii.

Journal Publications

Li, N., Cheung, K. F., Stopa, J. E., Chen, Y.-L., Hsiao, F., Vega, L., and Cross, P., April 2016. “Thirty-four years of Hawaii wave hindcast from downscaling of Climate Forecast System Reanalysis”, Ocean Modelling, Vol. 100, pp. 78-95, SOEST No. 9576.

Li, N., Cheung, K.F., and Cross, P., 2020. Numerical wave modeling for operational and survival analyses of wave energy converters at the US Navy Wave Energy Test Site in Hawaii. Renewable Energy, (accepted for publication).

Conference Proceedings

Li, N., Cheung, K.F., and Cross, P., 2018. Probabilistic distributions of extreme wave heights at the Wave Energy Test Site, Hawaii, proceedings of the 6th Annual Marine Energy Technology Symposium, Washington DC.

TASK 4: ENVIRONMENTAL IMPACT MONITORING AT WETS

This Task was initiated under contract Modification 009, (in September 2012) to: analyze environmental effects caused by WEC devices, namely OPT, the WEC devices deployed prior to the initiation of HINMREC; assess WETS site sensitivity, and; identify possible impacts on marine animals. Environmental impact studies included: evaluation of potential chemical and biogeochemical threats posed by various discharges associated with wave energy devices; general assessment of the impacts of ocean energy installations on marine life, including sediment transport effects, electromagnetic fields, and WEC acoustic signatures.

4.1 Acoustic Signature Measurements

The most substantial effort at WETS in the area of environmental monitoring has been that of measuring the acoustic signature of WECs as they relate to the ambient acoustic environment - to assess, primarily for future regulatory determinations, the degree to which wave energy systems contribute to the acoustic environment in a given area, and potentially impact behaviors of marine life. HINMREC has been conducting acoustic monitoring at WETS to measure both the ambient “soundscape” and the actual acoustic emissions from deployed WEC devices. Extensive underwater acoustic measurements and analysis during each WEC deployment resulted in important findings of very low-level acoustic signatures of the WEC devices tested to date. Acoustic data was collected using both fixed/bottomed and drifting devices. This allowed for the examination of both spatial and temporal acoustic variability in the acoustic environment – both in the ambient noise and in WEC signature data. Acoustic data was processed with the primary objective of deriving relevant source levels of sounds coming from the WEC devices and their associated moorings, while also comparing those emissions with ambient noise and other acoustic signals in the area.

Variability due to weather conditions, seasonal changes in ambient noise, and other factors has been examined, and continues to be under Navy funding.

HINMREC was tasked with making initial estimates of source levels of WEC devices when in operation at WETS. If source levels exceeded the maximum accepted level, given in the WETS EA as 151 dB re 1 µPa at 1m, by more than 3 dB for more than 5% of the operating time, HINMREC was required to immediately report the measured levels to the National Marine Fisheries Service (NMFS) via the Navy. By the conclusion of this project, this sound level threshold was not exceeded, or even approached.

Acoustic data was collected near each deployed WEC device on a nearly continuous basis, with an autonomous single hydrophone station associated with each berth at WETS. One system developed at UH, the Acoustic Monitoring Package, single channel (AMP-1), is shown in Figure 4.1. The stations were intended to be capable of deployments of up to three months duration (depending on duty cycles and sampling frequency), then recovered and redeployed with refreshed batteries and data storage. The positively buoyant systems were designed to keep the hydrophone acoustically decoupled from the bottom and away from the worst of the noise associated with snapping shrimp prevalent in Hawaiian waters. The devices were designed to resolve sounds in the frequency range of 20 Hz to 100 kHz. To obtain ambient conditions prior to WEC deployments, an initial AMP-1 deployment was begun in late January 2015.

Figure 4.1. The Acoustic Monitoring Package, single channel (AMP-1) was developed at the University of Hawaii (UH).

Due to the departure of key personnel from UH, this system was never deployed operationally at WETS. Instead, HINMREC strengthened its relationship with researchers at the University of Washington (UW) to address the challenge of collecting acoustic data in proximity to deployed WECs. The HINMREC/UW team ultimately developed two types of systems for this purpose - a bottom-fixed system for longer-term deployments to assess temporal variability of sound, and a drifting system for short-term deployments to assess the spatial variability of the sound field near deployed WECs. The drifting system, originally called the Surface Wave Instrumentation Float (SWIFT) is shown in Figure 4.2. The hydrophone was suspended 1.5m below the surface. Later, the UW engineers experimented with heave plates and drogues to achieve a compliantly coupled hydrophone/surface float configuration and reduce relative motion of the hydrophone in the water column. The SWIFTs were deployed with supporting instrumentation, including GPS, weather monitoring, and a camera system. Deployments were typically done over a period of a few days to a week to obtain a snapshot of the sounds produced by WECs and their mooring systems, as well as obtaining ambient acoustic data.

Figure 4.2. University of Washington SWIFT buoy being deployed at WETS in the vicinity of the Fred. Olsen Lifesaver WEC.

Figure 4.3. University of Washington SWIFT drifting hydrophone system, shown with a heave plate configuration on the left and with a drogue on the right.

Over time, continued efforts to reduce flow noise issues ultimately led to the next generation drifting systems, which are called Drifting Acoustic Instrumentation SYstems (DAISYs), equipped with suites of integrated instrumentation (Figure 4.4). Surface expressions included a meteorological station, tracking collars, an integrated GPS, 9-axis Inertial Measurement Unit (IMU), wireless and RF communication links, and condition health monitoring. The subsurface expression was instrumented with a board-level GPS, 9-axis IMU, pressure sensor, and an acoustic data acquisition system built around a hydrophone.

Figure 4.4. UW DAISY systems after a successful deployment at WETS near the modified Northwest Energy Innovations Azura WEC.

For stationary acoustic monitoring at the seafloor, two Seaspider (Teledyne Marine) platforms were developed by the UW/HINMREC team. These were intended to be deployed near deployed WECs for periods of approximately three months to provide long-term monitoring over changing sea states and seasons, as well as during a range of WEC operating conditions. Deployments have also been conducted when no WECs are deployed to obtain ambient noise data, and data with the mooring systems present, but in “no-WEC” configuration (as described later in the mooring discussion). The Seaspider platforms are gravity anchored tripods with three hydrophone recording packages, as shown in Figure 4.5. Acoustic packages used are from Loggerhead Instruments.

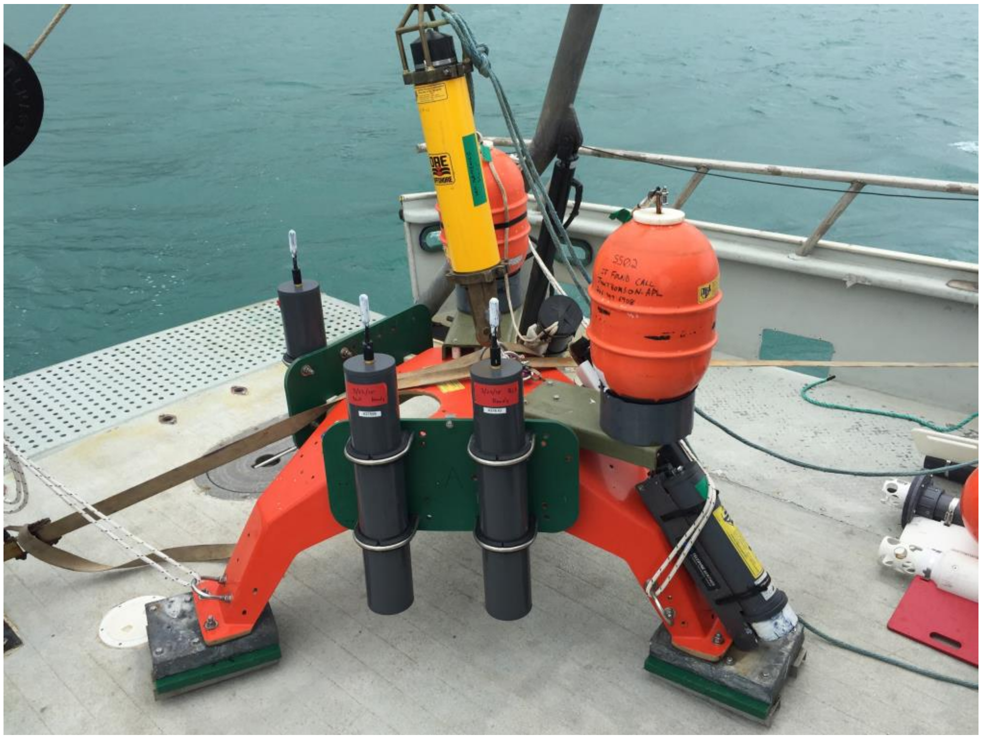


Figure 4.5. Loggerhead Instruments acoustic packages deployed aboard a Teledyne Seaspider package for deployment at WETS. System is configured with dual acoustic release system for post-deployment recovery.

To supplement these data collection efforts, acoustic modeling was conducted to estimate the acoustic field, to help clarify trends in the measured spatial distribution of sound, and to identify locations for future stationary hydrophone deployments that will result in higher signal-to-noise ratios (SNR) at frequencies of interest. A parabolic equation (PE) model, RAMGeo, was utilized to predict transmission loss in proximity to the Azura as a function of range, depth, source frequency, and metocean conditions. The initial simulations suggest rich spatial variability in transmission loss around the Azura. Repeating these simulations for other berths and devices and refining simulations will require further efforts to validate their accuracy. Validated models could then be used to select locations for future Sea Spider deployment that result in minimal transmission loss in frequency bands of interest to maximize signal-to-noise ratios. This work is detailed in the report “Transmission Loss Modeling, Acoustic Model Survey, and Implementation of Parabolic Equation (PE) Model” listed below under Reports and Publications, and is guiding planned acoustic system deployments under Navy funding going forward.

A low-cost alternative to the Seaspiders was designed and tested at WETS - a Subsurface Logger for Ocean Waves (SLOW). SLOW is an instrumented subsurface buoy designed for acoustic measurements of WECs at close range with minimal flow noise. The SLOW was tethered to the top of a subsurface buoy that was part of the Azura (and later 30m Lifesaver deployment and future Oscilla deployment) mooring system at the 30m berth and tested in January 2016. The SLOW was designed in response to challenges and costs with Seaspider deployments, and difficulty in re-deploying at precisely the same location from one deployment to the next - for repeatability of acoustic results. Because of the risk of entanglement with a WEC mooring system, a stand-off distance of at least 100m for the Seaspider is needed, and at this distance, the WEC can be difficult to distinguish from other ambient noise as the sound from WECs tested to date is of relatively low intensity. This complicates comparisons of WEC sound between deployments. Also, during long-period swell, significant flow-noise is produced and may mask WEC sound at frequencies up to 100 Hz. This test showed that while easier to deploy and recover than a Seaspider and allowing measurements closer to the Azura WEC, the SLOW did not effectively mitigate flow-noise below 50 Hz. The IMU data and video of SLOW motion captured by Sea Engineering divers suggests that the tether length (1m) is responsible for the limited flow-noise reduction. With larger, longer period waves, the SLOW records significant flow-noise. In addition, self-noise dominates the spectra in higher sea states and appears to be primarily caused by motion of the attachment hardware and possible impact of the SLOW with the subsurface buoy to which it is connected.

Acoustic measurements at WETS were used to characterize the temporal and spatial variations in sound produced by the Azura, modified Azura, and the two deployments of the Lifesaver. Temporal variations across a range of sea states have been quantified through the Seaspider deployments, and spatial variations in a range of sea states have been quantified by the drifting SWIFT and DAISY hydrophone systems. Both types of measurements have provided useful information, each with strengths and weaknesses. Stationary measurements with the Seaspiders provide well-resolved information during a wide range of WEC operating states, as well as observations of variability in the ambient soundscape (e.g., diurnal patterns in snapping shrimp, passing vessel noise, and changes in the acoustic signature of WETS mooring systems in varying sea states). Drifting measurements provide good spatial resolution and serve a valuable reconnaissance role for placement of the stationary packages. However, the sea states in which drifters can be recovered are limited to a subset of all WEC operating states and flow-noise masks WEC sound at frequencies below 100 Hz, adding additional value to the fixed/bottomed measurement data sets.

At frequencies less than 1 kHz ambient noise is dominated by the sound from wind and waves. At frequencies greater than 1 kHz, snapping shrimp dominate. Seasonally, humpback whales produce vocalizations that dominate in the range of 100 Hz to 1 kHz. Several anthropogenic sources are also present. The most persistent ambient noise is noise from the mooring chains used at the 60 and 80m berths. This sound is most intense around 1.5 kHz and is produced by chain motion from moorings that are not tensioned (as occurred in the past when a berth was unoccupied - this changed in June 2019 with the installation of a pretensioning hawser system called the “no-WEC hawser”, which will be discussed in the mooring section later in this report). Military aircraft traffic periodically contributes tonal sound around 100 Hz and vessel traffic periodically produces broadband, high-intensity sound that masks all other ambient noise when vessel range is less than a few hundred meters.

Against this background, the Azura produced a periodic “moan/whine” from its hydraulic PTO with time varying frequency. Multiple tones were present from 200 Hz up to 3 kHz. There are also occasional higher frequency squeaks and lower frequency muffled bangs/clanks from wave slap against the WEC structure’s spars and float. In summary, in the case of the Azura, the primary mechanism for sound production was the hydraulic generator, with secondary production from wave interaction. The Azura primarily produced sound at frequencies less than 3 kHz.

In the case of the Lifesaver, the dominant sound was mooring-chain noise, though it is unclear whether this originated from the Lifesaver berth or the unoccupied 80m berth. No sound has been definitively assigned to the power take-off component, suggesting that the Lifesaver would produce little identifiable sound. An abnormal operating state was also characterized, in which a damaged bearing in one Power Take-off (PTO) appeared to dominate the acoustic signature, clearly audible at higher frequencies (up to 5 kHz) and at ranges greater than 1 km, and reinforced the potential for acoustic monitoring to provide information regarding the health of marine energy systems. (Note: This was later determined to be caused from a problem in one of the Lifesaver PTO winch lines, although the point about marine energy device health monitoring remains valid.)

Measurements indicated that the sound from individual converters is of limited environmental consequence, with the intensity and frequencies of sound well below those produced by recreational watercraft and ocean-going container vessels at a range of several hundred meters. As expected for this scale of WEC, no operating states have been identified under which the acoustic emissions exceed regulatory thresholds. Each WEC does, however, produce sound that might be of environmental consequence in a large array. The Azura’s subsurface, hydraulic PTO produces a series of tones between 100 Hz and 1 kHz. Conversely, the LifeSaver PTO, located above the surface, appears to produce limited underwater sound when in normal operation.

In anticipation of the modified Azura deployment at the 30m berth, the Seaspider bottomed acoustic sensing station was deployed on 18 December 2017. It was recovered on 26 March 2018, at the end of its useful deployment life, thus capturing over one month of data in proximity to the modified Azura device. Additionally, UW DAISY drifters were deployed on 11,13, and 14 March 2018 to characterize sound in the vicinity of the modified Azura. Data analysis was completed in April, with little difference seen in acoustic signature as compared with the baseline Azura. A full report from UW was provided to the Navy sponsor as part of the modified Azura deployment report, and is available to DOE upon request.

Acoustic collection near Lifesaver, during the last deployment (at the 30m berth), consisted of UW DAISY drifters deployed during the last week of November 2018 and again in late January/early February 2019, and the Seaspider fixed platform deployed on 29 November 2018 – nominally for three months. Actual recovery of the Seaspider was delayed by weather, but was completed on 27 March 2019. Data quality is good, and analysis can be found in the report to the Navy. Procurement of two new Seaspider platforms and additional DAISY drifters is underway (with Navy funds), to enhance collection flexibility during the anticipated deployment of multiple simultaneous WECS at WETS in the 2021-2013 timeframe.

These acoustic surveys by HINMREC under DOE funding were completed with no-significant environmental impact observed. Azura and LifeSaver acoustic signatures were measured to be well below NMFS sound thresholds, and similar findings were observed during the follow-on deployments of both WECs. Ongoing acoustic measurements under Navy funding will occur - both in no-WEC scenarios and when one or more WECs are deployed at the site at a given time.

Reports and Publications

Technical Reports

Sea Engineering Inc., April 2015. WETS Task 1D and 1E Field Report - Acoustics, Second Hydrophone Deployment.

Sea Engineering Inc., July 2015. Sea Spider Hydrophone and SEI ADCP Deployment at 30m, Field Report.

Polagye, B., September 2015. Sea Spider Survey Report #1, Trial Deployment, Field Report.

Polagye, B., September 2015. Sea Spider Survey Report #2, Azura Pre- and Post-Installation, Field Report.

Polagye, B., September 2015. SWIFT Survey Report #1, Acoustic Characterization of Pre-Installation Conditions, Field Report.

Polagye, B., September 2015. SWIFT Survey Report #2, Acoustic Characterization of Azura Wave Energy Converter, Field Report.

Sea Engineering Inc., April 2016. WETS Task 1I Field Report – Acoustic Measurements with University of Washington, Hydrophone Drifts Around the Azura WEC.

Sea Engineering Inc., April 2016. WETS Task 1J Field Report – Acoustic Measurements with University of Washington, SWIFT Drifts Around the Azura WEC at 30m.

Sea Engineering, Inc., June 2017. Annual Report of the Wave Energy Test Site (WETS) at MCBH, Kaneohe 2016, (comprehensive report across several tasks).

Polagye, B., August 2016. SWIFT Field Survey #4, Initial Acoustic Characterization of Lifesaver Wave Energy Converter, Field Report.

Sea Engineering Inc., August 2016. WETS Task 1H Field Report – Sea Spider Hydrophone Recovery and Redeployment.

Sea Engineering Inc., August 2016. WETS Task 1G Field Report – Acoustic Measurements with University of Washington, SWIFT Drifts around the Azura WEC at 30m.

Polagye, B., Murphy, P., August 2016. Performance Assessment of Subsurface Logger for Ocean Waves (SLOW) Prototype.

Sea Engineering Inc., November 2016. WETS Task 1K Field Report – Sea Spider Deployment, 60M Berth.

Polagye, B., December 2016. SWIFT Field Survey #5, Compliantly-Coupled Hydrophone Systems, (Deliverable #15).

Polagye, B., January 2017. SWIFT Field Survey #3, Spatial Characterization of the Azura Wave Energy Converter, Field Report.

Murphy, P., Polagye, B., January 2017. Transmission Loss Modeling Acoustic Model Survey and Implementation of Parabolic Equation (PE) Model.

Sea Engineering Inc., June 2017. Annual Report of the Wave Energy Test Site (WETS) at MCBH, Kaneohe 2016.

Murphy, P., Polagye, B., June 2017. Two Sea-Spiders Field Survey Report #3.

Polagye, B., January 2018. SWIFT Field Survey #7, Surveys around Fred. Olsen Lifesaver.

Sea Engineering Inc., January 2015. Shore Side Report, 80m ADCP Deployment.

Polagye, B., March 2019. SWIFT Field Survey #8, Surveys around Fred.Olsen Lifesaver.

Polagye, B., Murphy, P., August 2019. WETS Acoustic Survey Final Report.

Conference Proceedings

Polagye, B., Murphy, P., Cross, P., Bethune, K., Vega, L., February 2016. Temporal and Spatial Variations in Sound Produced by a Wave Energy Converter, ICOE 2016, Edinburgh, UK.

Polagye, B., Murphy, P., Cross, P., Vega, L., January 2017, Acoustic Characteristics of the Lifesaver Wave Energy Converter, 12th European Wave and Tidal Energy Conference, Cork, Ireland.

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4.2 Electromagnetic Field Prediction, Measurement, and Protocols

The original HINMREC plan was to deploy, maintain and analyze data obtained with electric and magnetic field recorders designed to determine submarine power cable electromagnetic field (EMF) signatures at WETS. Testing would include data acquisition of time series of magnetic and electric measurements with equipment and cables both energized and de-energized.

However, it was determined by the U.S. Department of the Interior, Bureau of Ocean Energy Management (BOEM) and the University of California, Santa Barbara (UCSB), that submarine power cables operating at much higher power levels (~ 26 MW) than those expected from WEC devices tested at WETS (≤ 1 MW), do not negatively impact marine life such that performing measurements at WETS would not yield useful information. Further, a growing consensus in the marine energy field suggests that EMF is an insignificant factor in association with marine energy devices, particularly single devices of limited power production capacity, which is what will be tested at WETS. Therefore, this task was cancelled, and funds reallocated to acoustic emissions measurements. It is noted, however, that as new information becomes available and sensing techniques are developed, future measurements, such as those planned by Woods Hole under the DOE Triton program, will take place.

Major conclusions from the BOEM/UCSB report are:

- Submarine power cables transmitting electricity at power levels of 17 to 18 MW and as high as 26 MW do not affect the behavior of the fish (including some electro-sensitive species) and invertebrate species present in the area of the measurements and observations (February 2012 to October 2014).
- One meter away from the unburied energized cables the scalar magnitude of the magnetic field diminishes to background levels. Therefore, cable burial should only be considered to avoid damage from human activities (e.g., fishers, anchoring etc.).

References

[1] Love, M. S., M. M. Nishimoto, S. Clark, and A. S. Bull. 2016. Renewable Energy in situ

Power Cable Observation. U.S. Department of the Interior, Bureau of Ocean Energy Management, Pacific OCS Region, Camarillo, CA. OCS Study 2016-008. 86 pp.

[2] Personal correspondence (June 2016) Vega with C. Blake Hebert, PE. Electrical Engineering Advisor CSC-Electrical Function, ExxonMobil Production Company. USA.

4.3 Ocean Current and Wave Measurements with ADCPs

Since HINMREC was charged with the independent evaluation of WEC device performance, device power output (kW) is measured as a function of wave parameters, obtained from wave measurement devices. The primary objective under this task was to provide statistically significant comparisons between the industry standard devices, namely a Datawell Directional Waverider© buoy, and the latest generation Acoustic Doppler Current Profilers (ADCPs). ADCPs can be deployed on the seabed, directed up to the surface, and through post processing can detect the essential characteristics of the surface wave field. However, how well these data compare with Waverider© was not well documented in the literature.

For this reason, HINMREC contracted with Sea Engineering Inc. to deploy a state-of-the-art ADCP, a Teledyne RDI Sentinel V100, to compare measurements with the Waverider© buoy (CDIP#198) that is maintained by UH and PacIOOS. The ADCP was deployed on November 13, 2014, on the seabed, looking up at the surface, approximately 400 m from the WETS Waverider© buoy and along the same 80m depth contour (Figure 4.6).

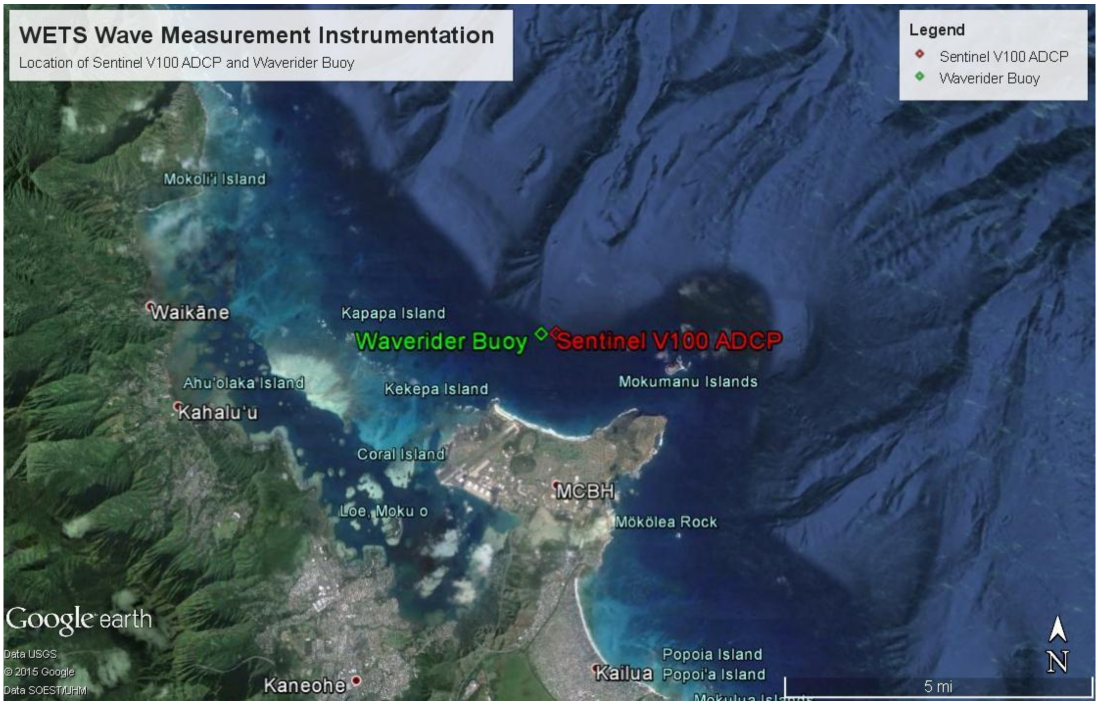


Figure 4.6. Location of the wave measurement instruments deployed at the WETS 30m berth.

The latest generation ADCPs, like the RDI Sentinel V100 installed at WETS, use five beams instead of the traditional four and software that has been updated to resolve some of the issues identified during previous field tests.

Comparison between Waverider© buoys and earlier versions of ADCPs were performed based on field data obtained at shallower depths. However, previous work was performed with ADCP devices installed at depths less than 45 m and separated by as much as 30 km from the Waverider© , such that data had to be transformed to different depths using linear theory correction for shoaling and refraction effects. It was learned that estimates of wave parameters obtained with those ADCPs correlated favorably with those obtained with Waveriders© in waters shallower than about 20 m. In general, significant wave height, peak frequency and mean direction parameters were in agreement but directional spreading was not. The directional information is not an issue for some type of WEC devices (e.g., heave only point absorbers) but is important and required for the control of others that need to also tune additional degrees-of-freedom (e.g., their roll, pitch, surge and sway) to the wave environment.

One of the features of the Sentinel V100 ADCP is its ability to measure wave statistics using a fifth vertical beam (in addition to the four off-vertical beams) to improve the accuracy of the measurements and provide high resolution surface tracking. The device uses a vertical acoustic beam to measure the distance to the water surface. Sound waves reflect off the water surface and the time a reflection takes to return to the ACDP is used to determine the distance to the surface. Accurate wave statistics can be computed from the measured water surface elevation record. An ADCP relies on the Doppler Effect to determine the water currents through the water column. The direction of current can be determined by using three or four acoustic beams. The acoustic reflection of a beam that is up current from the ACDP will arrive before the reflection of a down current acoustic reflection. With the reflection return timing of multiple beams, the direction of waves and currents can be calculated.

By comparison, the Waverider© buoy uses sensitive accelerometers to determine the motions of a moored buoy. The buoy is designed such that the mooring line and anchor have minimal impact on the motion of the buoy. The motion of the buoy is representative of wave motion and is used to calculate wave conditions and parameters.

Measurements from the Sentinel V100, deployed from November 2014 through April 2015, and the Waverider© had a relatively close correspondence (Figure 4.7).

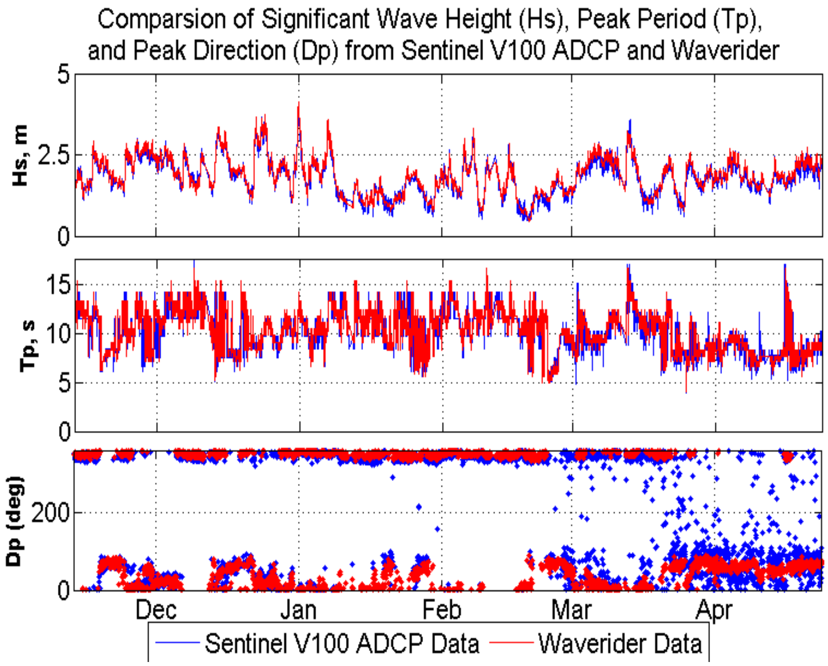


Figure 4.7. Time series of the ADCP and Waverider© at WETS (November 2014 through April 2015).

The ADCP proved to be as accurate as the Waverider© in the estimation of wave height, based on statistical metrics of the ADCP measurement error in relation to the standard provided by the Waverider©, with the significant wave height correlation estimated at 0.96 for the entire period.

In relation to the Waverider©, the ADCP period and direction estimates were not as precise as the wave height estimates, as represented by the peak period and peak direction. The correlations were 0.71 and 0.59, respectively. The lower ADCP correlation of the peak direction is due to the large range of directional values, and the large jumps in direction – from 360° to 50° – that can occur quickly at WETS as a swell event subsides and trade wind seas become dominant. More detail is available in the reports listed below.

The ADCP data was available to the tenant at that time (NWEI), and was used in conjunction with the Waverider© records (Task 3.2.1) in assessing the Azura power performance (Task 5.2.2) and for the sediment transport analysis (Task 4.4).

Numerous additional ADCP deployments were done for HINMREC in the years since this comparative analysis was done. This has built up a good data set to document currents at WETS, and has, when deployed, provided a backup data set to the Waveriders for wave conditions. In December 2017, a different ADCP was deployed at the 60m site, and was recovered in March 2018. During recovery, one of the sensors was damaged, and after repairs completed by the manufacturer, the ADCP was redeployed in May 2018. The final ADCP deployment was concluded with recovery on 3 July 2019. ADCP data collection is no longer being conducted at WETS, with the end of HINMREC funding for this function.

Reports and Publications

Technical Reports

Sea Engineering Inc., June 2012. Kaneohe Wave Energy Test Site Acoustic Doppler Current Profiler Data Report.

Sea Engineering, Inc., May 2015. Task 4A, Wave Energy Test Site Comparison of Waverider© Data and Sentinel V100 ADCP Data, Report.

Sea Engineering, Inc., September 2015. Task 4B, Wave Energy Test Site Comparison of Waverider© Data and Sentinel V100 ADCP Data, Report.

Sea Engineering, Inc., L. Vega, 2016. Wave Measurements at WETS: Comparison of Waverider© and ADCP in-situ Records.

Sea Engineering, Inc., September 2016. Task 4C, Wave Energy Test Site Sentinel V100 ADCP Data Analysis at 30m Site.

Sea Engineering, Inc., March 2017. WETS Task 4E: ADCP Deployment (and Sea Spider Hydrophone Deployment) Field Report.

Sea Engineering, Inc., June 2017. Annual Report of the Wave Energy Test Site (WETS) at MCBH, Kaneohe 2016, (comprehensive report across several tasks).

Sea Engineering, Inc., August 2017. Task 4D Report - ADCP Data Analysis at WETS 30m Site.

Sea Engineering, Inc., August 2017. Task 4G Report - ADCP Data Analysis at WETS (70m Depth).

Sea Engineering, Inc., August 2017. Task 4H Report - ADCP Data Analysis at WETS (70m Depth).

Sea Engineering, Inc., March 2018. Task 4I Report - ADCP Data Analysis at WETS (70m Depth).

Sea Engineering, Inc., June 2018. Task 4J Report - ADCP Data Analysis at WETS (70m Depth).

Sea Engineering, Inc., December 2018. Task 4K Report - ADCP Data Analysis at WETS (70m Depth).

4.4 Sediment Transport Analysis and Field Surveys

Seafloor observations at WETS were focused on the anchor base structures and interactions with the natural seafloor sediment movement at the 60 and 80m berths. (The 30m berth is characterized by a hard bottom, with only a thin veneer of sand, and very sparse corals.) These were monitored with periodic surveys conducted with an ROV. The sediment distribution (Figure 1.2 in Task 1) was periodically reexamined to determine whether the presence of the moorings, or of the devices themselves, had a measurable impact on sediment distribution over time. A combination of core samples, fixed measurement staffs, and scour cylinders was used.

The sediment staffs and two scour measurement cylinders were installed at the 60 and 80m berths in an effort to investigate natural sediment transport and scour. The sediment staffs were marked in centimeter graduations. The scour cylinders consisted of thin walled sheet metal cylinders approximately 12" in diameter, and 16" high. The cylinders were partially filled with concrete from 4" to 10" from the bottom of the cylinder. When placed on the seafloor, the cylinders sunk into the sediment to the level of the concrete, allowing for observation of scour.

Observations of the sediment staffs indicated that there was little natural sediment transport in the area. Survey of the sediment staffs, however, revealed significant influence of marine biological activity that obscured the marking increments. The base of the staffs at the 80m site were undermined by marine biological activity and there was a depression surrounding the northeast staffs. The extensive marine growth at both locations rendered further measurement invalid.

Observations of the scour cylinders indicated there was scour at both locations such that eventually one of the cylinders toppled over due to excessive scour. Thus, ultimately, both the sediment staffs and scour cylinders proved ineffective at quantifying sediment transport in the area. Therefore, a determination was made that, going forward, surveys would be done qualitatively during regular ROV inspections of the mooring components by examining the sediment around the anchors and sinker-weights of the deep water mooring locations.

Based on these HINMREC field surveys, it can be concluded that while measurable current-induced sediment transport does occur in the area of the 60m and 80m berths, it is insufficient to impact the performance of the cost-effective drag embedment anchors used at these berths. Further, the overall distribution of sand in the vicinity of the deep berths has not significantly changed in the years since the deep berth moorings and cable anchors were installed (September 2014).

Reports and Publications

Technical Reports

Sea Engineering, Inc., December 2014. Sediment Transport Analysis, Task 1A, Field Report.

Sea Engineering, Inc., December 2014. WETS Task 3A Sediment Transport Analysis, 80m and 60m anchor location sediment transport deployment, Field Report.

Sea Engineering Inc., July 2015. WETS Task 3B Sediment Transport Analysis, 60m and 80m Mooring Locations, Field Report.

Sea Engineering, Inc., April 2017. WETS Task 3D Sediment Transport Analysis Field Report, ROV Monitoring, (estimate of sedimentation or scour around the objects).

Sea Engineering, Inc., June 2017. Annual Report of the Wave Energy Test Site (WETS) at MCBH, Kaneohe 2016, (comprehensive report across several tasks).

4.5 Ecological and Seawater Chemical Analysis Surveys

HINMREC performed and documented six quarterly ecological and seawater chemical analysis surveys, completed from 2014 through 2017. The documented methodology used by NAVFAC biologists to perform ecological dive surveys, during the previous testing phase (2003-2011) of the Ocean Power Technologies (OPT) point absorber, was revised and used to continue the survey process and augment the unique database for the site under HINMREC funds.

Quarterly ecological surveys around the 30m berth included a fish count and replicate quadrants in two locations near the anchors. Also two replicate transects were conducted along the cable route. One 50 meter transect was completed from the shelf (~12 meters deep) along the cable towards shore, and another transect at the base of the shelf (~24 meters deep) and continued up the slope to the shelf.

Water sampling and subsequent seawater chemical analysis were conducted at all three WETS berths to determine if any the potential changes in seawater composition occurred due to the presence of WEC devices. The following constituents were sampled at near bottom, mid, and upper water levels: Dissolved Oxygen, Salinity, Temperature, Turbidity, and pH.

There was no evidence of significant environmental impact from all surveys conducted by NAVFAC (2003-2011) and by HINMREC under DOE funding (2014-2017). The latter are listed below. It is noted that the Navy continues to directly fund ecological dives at WETS (not through HNEI). These now represent an extensive history since the early days of OPT testing in 2003. Detailed reports have been produced by the Navy to document these surveys.

Reports and Publications

Technical Reports

Sea Engineering Inc., March 2015, WETS Ecological Survey Field Report Diving #1.

Sea Engineering Inc., April 2015, WETS Ecological Survey Field Report Diving #2.

Sea Engineering Inc., October 2015, WETS Ecological Survey, Field Report Diving #3.

Sea Engineering Inc., February 2016, WETS Ecological Survey Field Report Diving #4.

Sea Engineering, Inc., June 2017. Annual Report of the Wave Energy Test Site (WETS) at MCBH, Kaneohe 2016, (comprehensive report across several tasks).

TASK 5: WAVE ENERGY CONVERSION DEVICE PERFORMANCE

This task was initiated under contract Modification 009 (11 September 2012), to implement a series of new activities in support of operations at WETS, under the working partnership between Navy and DOE. A major role was for HINMREC to assess the power performance of electricity producing WEC devices.

HINMREC contracted with DNV GL for support in developing and providing operational guidelines for use by WEC developers testing devices at WETS. The purpose was to identify the main activities, processes and controls to enable safe marine operations at WETS; provide overviews of the main safety and operational issues to consider at the various stages of the projects, and; provide checklists to assist both HINMREC and device developers in the preparation for and execution of daily marine operations.

HINMREC designed and implemented a methodology for WEC performance analysis and verification under a testing protocol (Task 5.1). A WEC performance numerical model was developed to allow for virtual testing, modification, and optimization of WECs prior to field testing (Task 5.2.1). The numerical model allows an efficient and cost-effective preliminary test to guide the field testing, and is available to designers and developers.

The required data acquisition and data analysis protocols were designed and documented, including instrumentation acquisition, deployment, and maintenance during the WEC device testing phase (Task 5.2.2). The performance metrics included a Power Matrix designed to tabulate the relationship between power output (kW) and significant wave height (Hs, m) and energy period (Te, s). The wave parameters were defined in the spectral treatment of sea surface elevation time series (also referred to as time history records).

HINMREC also conducted a series of periodic surveys to assess the durability of the WEC devices under testing at WETS as well as the durability of the mooring systems and the submarine power cables (Task 5.2.3). These tasks led to development of methodologies used at WETS and available for use elsewhere, in the evaluation of technical aspects related to the operation of WEC devices.

5.1 WETS Test Protocols and Data Acquisition System

With support from DNV GL, HINMREC developed wave energy test protocols for use in the evaluation of WEC system performance at WETS, incorporating both environmental and WEC power data. The test protocol allowed time history records of WEC device power output to be obtained as a function of environmental input (wave and current conditions). The protocol was needed to collate all relevant data, and was defined based on protocols available in existing international test centers, EU initiatives, and similar activities underway under the International Electrotechnical Commission (IEC), IEC –TC-114, and NREL working groups.

The required electrical instrumentation was also acquired. The ocean current profile in the vicinity of the test devices was recorded with a dedicated instrument (ADCP, under Task 4.3), and standard meteorological parameters per World-Meteorological-Organization (WMO) specifications were available through the Automated-Surface-Observing-System (ASOS) installed at MCBH. In this way, the combined influence of the ocean currents and local meteorological conditions on the performance of the installed WEC devices was assessed.

HINMREC was a member of the IEC and NREL working groups, and participated in the design and implementation of the IEC Technical Specification (TS) protocol that is used to provide an independent evaluation of WEC device in-water performance [IEC/TS 62600-101:2012, Marine energy - Wave, tidal and other water current converters - Part 100: Electricity producing wave energy converters – Power performance assessment.] The test protocol and associated data acquisition system was designed, along with suitable measures for uncertainty, to estimate device performance by recording the time series of sea surface elevation (waves) and power output (kW) at the device generator terminal.

No device subsystem parameters were recorded by HINMREC, as only the environmental input (waves) and the device output (power at generator terminal) were required. The device subsystem and design details are generally proprietary. The WEC developer, however, is able to, and generally does, choose to incorporate a much more complete suite of subsystem instrumentation data feeds. Data acquisition systems were designed to document device performance by recording time series of sea surface elevation (waves) and power output at the device generator terminal, at a point where the output is in the form of AC at 60 Hz at a grid connection voltage.

Reports and Publications

Technical Reports

GL Garrard Hassan, May 2013, Test Protocols Final Report, Hawaii National Marine Renewable Energy Center WEC Ocean Testing.

GL Garrard Hassan, July 2013, Operational Documentation, Hawaii National Marine Renewable Energy Center - WEC Testing.

5.2 Device Performance Analysis

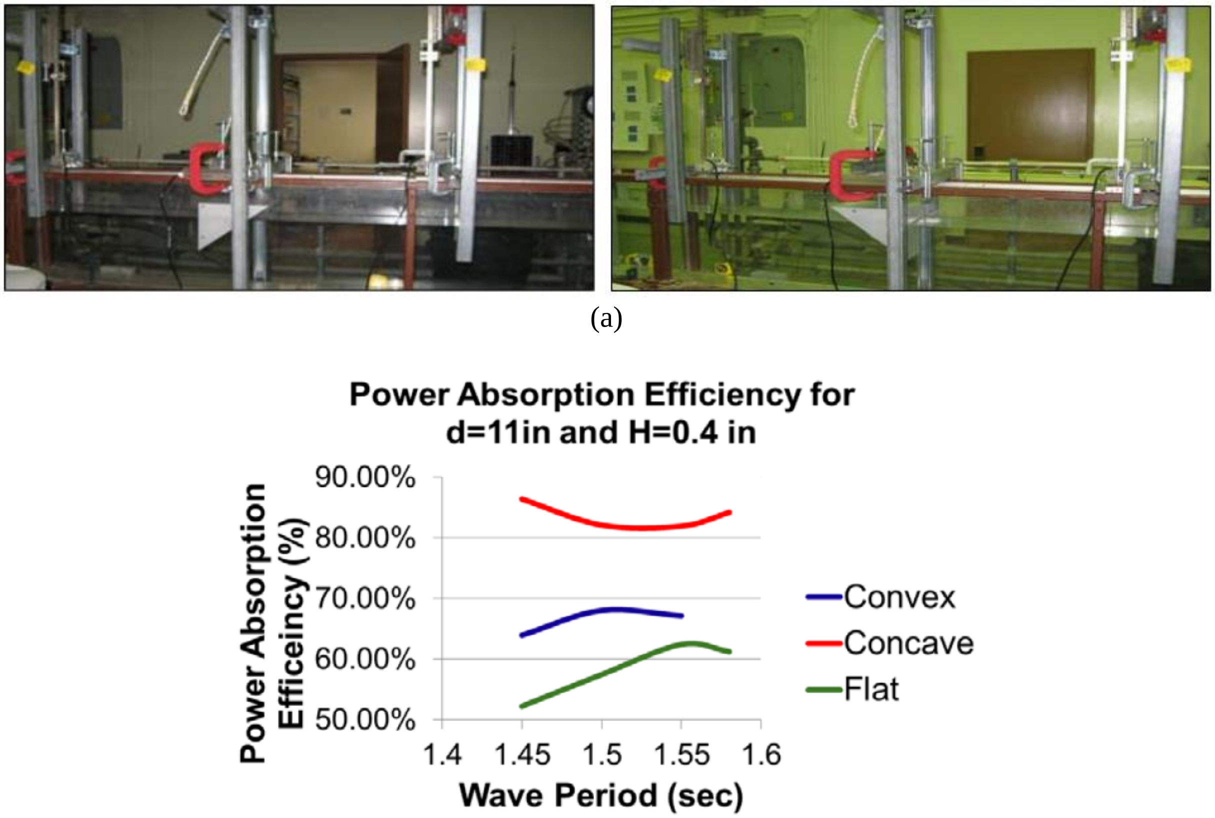
HINMREC's role under this task was to provide an independent assessment of the power performance of WEC devices tested at WETS. A summary of the three subtasks is provided, WEC Performance Modeling, WEC Testing Phase Data Analysis, and Hardware Reliability Surveys.

5.2.1 WEC Performance Model

This project made use of proven seakeeping analysis numerical models. Complementary wave tank studies were also conducted early in the program, along with numerical modeling to support the field testing in an effort to optimize WEC device development. Two primary objectives were pursued: 1) refinement of numerical simulation packages to predict dynamic loads on floating and submerged structures and assess the performance of single wave power devices and interacting arrays of these devices; and 2) scale tests in an existing UH wave tank at the UH Department of Civil and Environmental Engineering, including a 12.2 m (l) x 1.2 m (w) x 0.9 m (d) wave tank/wave generator (equipped with a towing carriage for OTEC studies).

The wave flume has an advanced computer-controlled wave maker that can generate periodic waves, solitary waves, conoidal waves, breaking waves, and also irregular waves to better simulate the ocean wave field. Instrumentation includes multiple wave gauges and data acquisition systems, a 3-D Laser Doppler Velocimeter (LDV), a 3-D Particle Image Velocimeter (PIV), video cameras, high speed cameras, and flow meters.

Experiments were conducted under different wave conditions to examine single devices and series of devices arranged in different patterns. In one of these experiments, the geometry of a two-dimensional, single, heaving body was optimized for maximum power absorption with regular, harmonic, linear, incident waves. The research was conducted through both wave tank experiments and numerical simulation. Numerically the optimum shape for power absorption efficiency was found using the software AQWA, which was then verified experimentally, (see Figure 5.1).



(a)

(b)

Figure 5.1. Experiments carried out at UH to optimize the shape of a heaving floater for maximum power absorption. (a) Experimental setup. (b) Summary of results from experiments, showing the concave face has the highest efficiency.

The concept of using man-made wave focusing structures to enhance the performance of WEC devices by focusing waves to increase their amplitude by propagation over a submerged structure was investigated. Laboratory experiments were conducted to explore the possibility of developing practical wave focusing lenses that could be deployed with various wave power devices in the ocean. Wave tank information was made available to developers and in a report posted on the HINMREC web page.

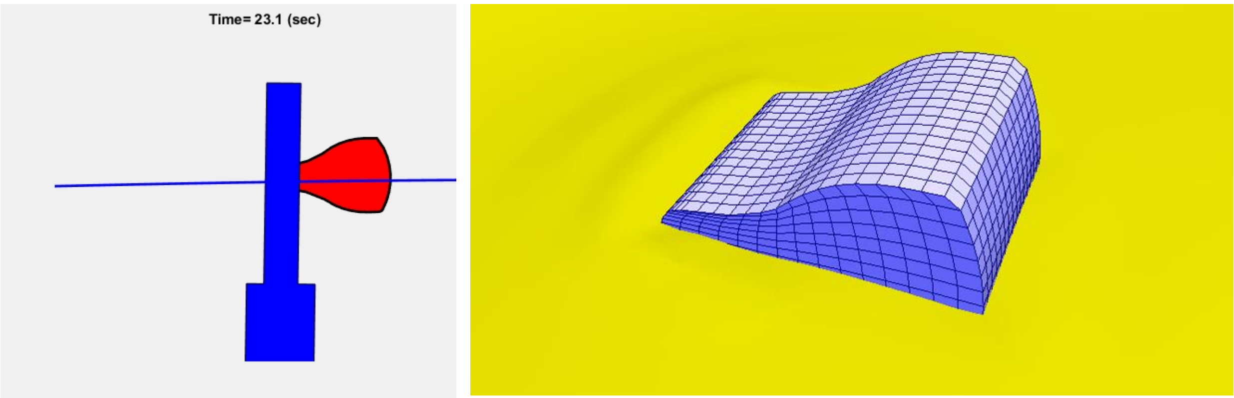
After September 2011, small-scale tests of prototype devices in the UH wave tanks were discontinued, since it was determined that OSU, the US Naval Academy, and others have superior and larger facilities better suited to this sort of work.

A numerical model was developed to simulate wave tank analysis, to allow virtual testing, modification, and optimization of WECs in an efficient and cost-effective way, prior to field testing. This model utilized proven seakeeping analysis numerical models, based on finite-volume discretization.

Verification of HNEI's WEC performance model entailed using DNV GL's in-house WEC performance and loading analysis tool WaveDyn, which was developed specifically for WECs. The tool allows for flexible, multi-body modelling of a wide range of WEC concepts in time domain simulations, and couples loading from critical areas including hydrodynamics, power take off, and moorings. DNV GL simulated a range of generic WEC models in conditions representative of the WETS site in order to provide a database of results for use by HNEI. Extreme loads of a WEC model test case were also assessed for WEC devices using a variety of methods.

Modeling efforts were geared towards the generation of a theoretical Power Matrix (electrical output as a function of significant wave height and energy period) to be compared to the Power Matrix based on field data recorded during operations of the WEC devices, starting with the Azura at WETS.

Power prediction of Azura was conducted using WEC-Sim, developed by NREL. The necessary hydrodynamic coefficients, required as inputs to WEC-Sim, were generated using WAMIT™ software and OpenFOAM CFD packages for the baseline case. Extensive numerical modeling of the device was carried out in WEC-Sim to tune the numerical model to match experimental data of the device measured at WETS. WEC-Sim requires model-basin or field data to be calibrated for a specific WEC device configuration. Figure 5.2 shows the Azura device modeled in WecSim and OpenFoam solvers.



(a) (b)

Figure 5.2. (a) Azura device modeled in WEC-Sim, showing the instantaneous free surface, float and top of the spar. (b) Float undergoing heave oscillations in OpenFOAM CFD solver.

Although the WEC-Sim model is not calibrated for an Azura-like device retrofitted with a heave plate, preliminary predictions were made for such a configuration (i.e., modified Azura). This was done to support NWEI in the implementation of future at-sea tests with NAVFAC funding.

Under ONR funding, a license for Flow3D CFD software, a flow solver for real flows, was obtained. This software solves the Navier-Stokes equations that include viscosity and non-linearity. This was done in an effort to set up a Numerical Wave Tank (NWT). NWTs are required to model realistic fluid flow phenomena. In the case of the modified Azura device, Flow3D was used to calculate the viscous drag properties of the device. Figure 5.3 shows the full-scale spar undergoing heave oscillation tests in the NWT; from these tests the drag can be estimated.

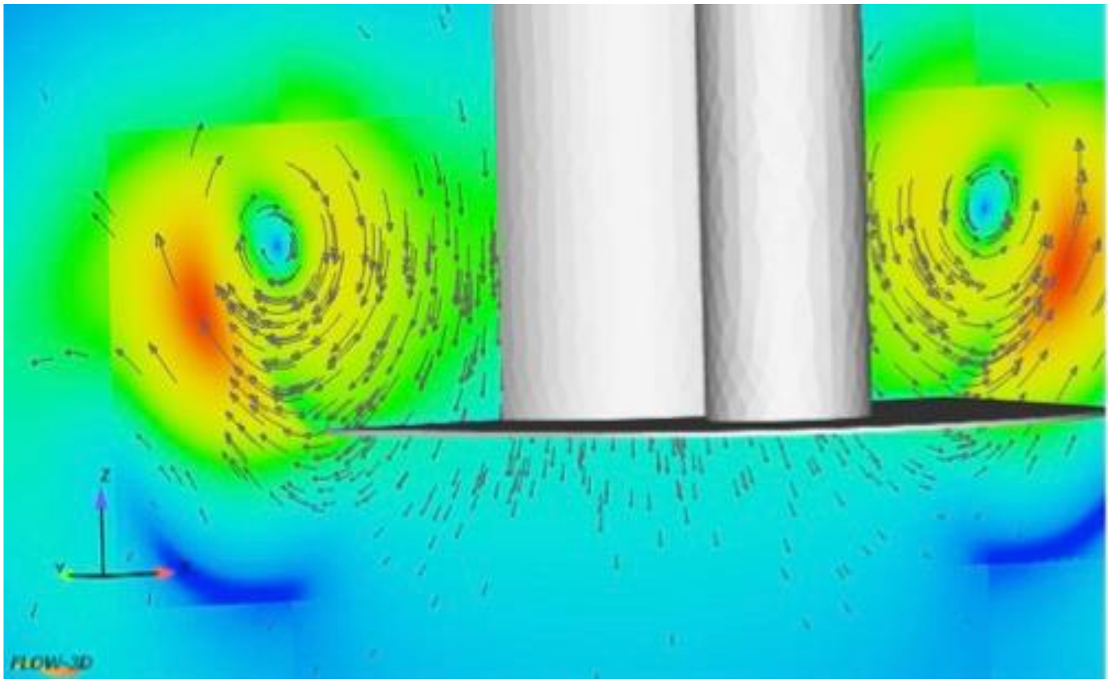


Figure 5.3 Snapshot of full size spar of Azura undergoing heave oscillation tests in numerical tank. The central vertical plane in the fore-aft direction is colored by velocity magnitude. Also shown are velocity vectors.

Also under ONR funding, modeling work was continued and expanded beyond what was done under HINMREC, and the Azura and modified Azura numerical models were completed. The comparison between experimental data and numerical results for heave motion Response Amplitude Operator (RAO), in the case of the modified Azura device, is shown in Figure 5.4. This figure is representative of the effect of viscous drag parameters on the motion characteristics of the device.

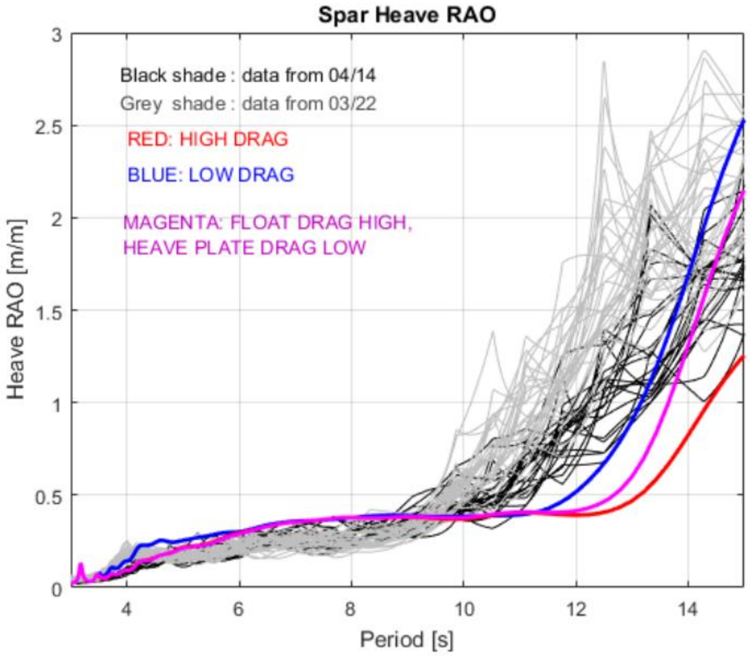


Figure 5.4 Heave RAO from trials and numerical models. Grey and black shades represent experimental data from different dates. Other colored lines represent numerical results with different viscous drag for spar and float.

Wave arrays were also modeled, to determine the required separation distances between devices. Under NAVFAC funding, hydrodynamic modeling of WEC performance and WEC mooring systems has expanded. Foundations and skills developed during HINMREC hydrodynamic numerical modeling studies have formed a solid basis on which to build this growing modeling capability.

Reports and Publications

Technical Reports

GL Garrad Hassan, March 2016, WEC Performance Model Verification - Progress Report #1,

Hawaii National Marine Renewable Energy Center, WEC Ocean Testing.

GL Garrad Hassan, April 2016, Testing Support – Progress Report #1, Hawaii National Marine Renewable Energy Center, WEC Ocean Testing.

GL Garrad Hassan, June 2016, WEC Performance Model Verification – Progress Report #2, Hawaii National Marine Renewable Energy Center, WEC Ocean Testing.

Journal Publications

Nihous, G.C., August 2013. Maximum wave power absorption by flexible line attenuators, Applied Ocean Research 43, 68–70, doi.org/10.1016/j.apor.2013.08.003.

Nihous, G.C., April 2014. Maximum wave power absorption by slender bodies of arbitrary cross sections in oblique seas, Applied Ocean Research 47, 17–27, doi.org/10.1016/j.apor.2014.03.007.

Nihous, G. C., May 2014, The method of imbedded Lagrangian element to estimate wave power absorption by some submerged devices, Journal of Marine Science and Application, 13, 2, doi:10.1007/s11804-014-1247-9

Rajagopalan, K., Nihous, G. C. 2016. Study of the force coefficients on plates using an open source numerical wave tank, Ocean Engineering, 2016, 118.

Conference Proceedings

R. Hager, N. Fernandez, M.H. Teng, September 2011. Geometric Optimization of a Single, Two-Dimensional, Heaving Body of Power Absorption Efficiency, OCEANS'11 Conference, (poster).

Nihous, G. C., Rajagopalan, K., Vega, L. A., April 2015. Development of a Numerical Wave Tank to Support WETS Activities, 3rd Marine Energy Technology Symposium (METS), Washington, D.C.

Rajagopalan, K., Cross, P., Nihous, G., June 2019. Numerical Modeling Research at the US Navy Wave Energy Test Site, Honolulu, Hawaii, International Society of Offshore and Polar Engineers (ISOPE) Honolulu.

Master's Thesis

R. Hager, August 2012. Geometric Effects on Maximum Power Absorption Efficiency for a Single, Two-Dimensional Heaving Body, Thesis, Master of Science in Civil Engineering, University of Hawaii.

5.2.2 WEC Testing Phase Data Analysis

Time series of WEC device power output as a function of environmental input (wave and current conditions) under the test protocol for WETS were recorded and analyzed. Data acquisition and analysis was conducted during field testing of the WEC devices at the three WETS berths. Tenants at WETS were required to provide power output data at the generator terminal.

The device capacity factor was evaluated as a function of wave resource data. The device performance data obtained at WETS has multiple uses for: device developers who want to validate the performance of their WEC; investors who want to assess the performance of a device developer's WEC; and, eventually project developers who want to assess the performance of their project against manufacturer's claims. A process was established to determine the type of data that was made available in the public domain, in agreement with all parties (e.g., Navy, DOE and the developers). The process made use of methods and software to non-dimensionalize data for protection of proprietary information. Cooperative Research and Development Agreements (CRADA) were negotiated and implemented with WEC developers before testing at WETS.

The data acquisition, analysis, and the Power Matrix report for the first deployment of the Azura device over 4-seasons was completed in 2016 and supplied to DOE. A similar report was prepared for the second deployment, done under Navy funding, and provided to Navy. These reports are not shared publicly due to the proprietary nature of the performance data.

Data acquisition for the first Lifesaver deployment was completed in April 2017 with one-year long records. However, due to the many interruptions in data collection associated with Lifesaver, it was difficult, and misrepresentative, to produce a proper Power Matrix (or matrices) for the Lifesaver's first deployment. These interruptions were caused by various hawser (horizontal mooring lines from permanent surface buoys to the device), and PTO winch line failures. NAVFAC approved funding for additional tests with improved (reduced) hawser pre-tension, and under that Navy-funded project to redeploy the device, emphasis was placed on generating power matrices to augment the data collected previously and yield meaningful conclusions as to power performance of the device.

Based on lessons learned from the HINMREC-supported first Azura deployment, a proposal was put forward to NAVFAC, and funding received for the redesign and testing of the modified Azura. The device was deployed and power matrices developed. Power performance data collection from the modified Azura deployment began on 20 February 2018 and concluded in mid-August 2018 when the device was recovered. A robust suite of performance data, as well as device motion data for comparison with numerical modeling predictions, was collected.

Conference papers comparing the motions/performance of the baseline and modified Azura against model predictions were completed and are listed in the Reports and Publications section below. In short, while that device did exhibit improved motions of the float relative to the spars, that did not equate to improved power performance. One of these papers analyzing this result was presented at the European Wave and Tidal Energy Conference in Naples in September 2019. A key conclusion is that, although the intended improvements in relative motion between the device float and spars were achieved, the device PTO was unable to convert the added torque from the float into electrical power generation. Final reporting on Azura power performance was delivered to DOE. The final report to NAVFAC on the modified Azura power performance may be available to DOE by request, along with the final reporting on the Lifesaver power performance which is ongoing at the time of this report.

Fred. Olsen, Ltd. shares their power performance data from the WETS deployment openly. These data can be found at www.boltwavepower.com (Figure 5.5 and 5.6).

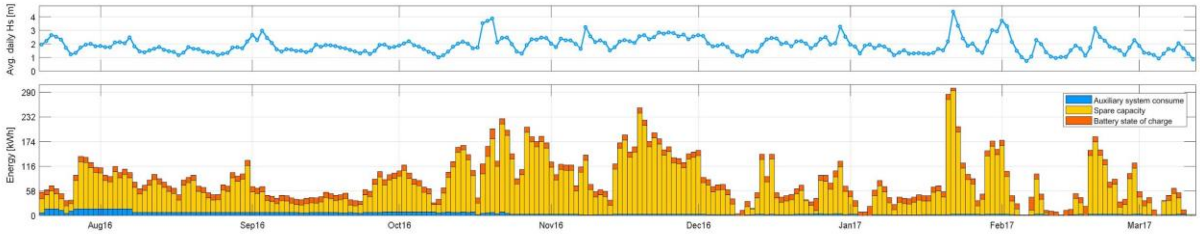


Figure 5.5. Energy production from the LifeSaver WEC, during the first deployment (July 2016 through March 2017).

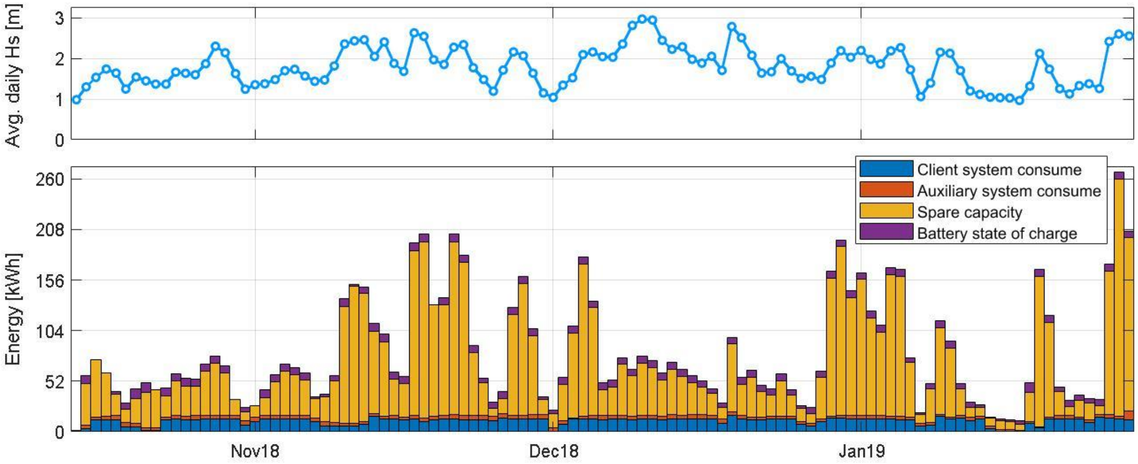


Figure 5.6. Energy production from the LifeSaver WEC, during the second deployment (October 2018 to through January 2019). Also shown in this plot is the power consumption of the UW AMP system (in blue), demonstrating that the Lifesaver provided, on most days, far more power than that system required for operation.

Reports and Publications

Conference Proceedings

Lettenmaier, T., Ling, B.., Vega, L. A., Nelson, E., May 2017. Open Ocean Testing of the Azura Prototype Wave Energy Converter in Hawaii, 2017 METS (Marine Energy Technology Symposium), Washington DC.

Rajagopalan, K., Cross, P., Ling, B.., Lettenmaier, T., September 2019. AZURA WEC power performance - a preliminary comparison of trial data and numerical modeling results, European Wave and Tidal Energy Conference, Naples, Italy.

5.2.3 Hardware Reliability Surveys

HINMREC conducted a series of periodic surveys to assess the durability of the WEC devices tested at WETS, as well as the durability of the mooring systems and the submarine power cables. Surveys encompassed above water visual inspection and below water inspections, utilizing both divers and ROVs. These surveys were conducted monthly for the first quarter after device installation. If no significant issues were observed during the first months inspections, the inspection frequency was then done on a quarterly basis. (The realities of crew availability and, especially, suitable weather tend to make these intended schedules only a loose plan. Over time, this intended frequency of inspection is close to what has been achieved, but given the need to sometimes wait weeks for suitable weather for an inspection, actual frequency is much less regular.)

At the 60 and 80m berths, periodic dive surveys in the vicinity of the anchors and inspections of the mooring lines and submarine power cables were conducted. ROV inspections of the anchors and mooring hardware located below diver depth was conducted roughly monthly for the first 3 months and then quarterly (with the caveat above). These inspections helped focus on areas of abrasion and wear, and helped to identify maintenance requirements. Lessons learned were documented and the information was used to improve future designs. These inspections and related experiences under the HINMREC program have informed the ongoing inspection work at WETS under Navy funds.

The Azura, as well as the second Lifesaver deployment, were at the 30m berth, and periodic diver inspections to 30m depth were conducted. This included inspection of the devices, mooring lines, subsurface floats, and, in the case of the Lifesaver, PTO winch lines to the seabed. The inspections and documentation were used to monitor and measure the wear associated with operation of WEC devices. The Azura operated with 96% system availability for the duration of its first deployment (Figure 5.7).

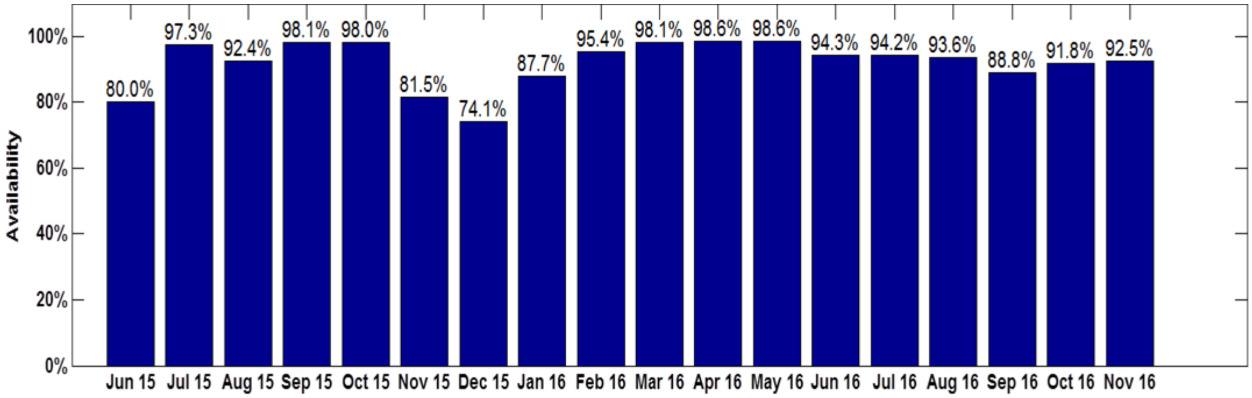


Figure 5.7. Azura availability for each month in the deployment (June 2015 through November 2016).

Diver surveys were conducted during the modified Azura deployment, with the last survey shortly before the device was recovered. The modified Azura functioned throughout the deployment with no need for maintenance intervention. The device remained fully functional, and the moorings were sound throughout.

In the case of the Lifesaver device, which was initially deployed at the 60m berth, surveys included ROV inspections below 30m depth in addition to diver inspections to 30m. Similar inspections were conducted during the second Lifesaver deployment. Device reliability was excellent through the first 50 days, after which a combination of PTO mooring (rock bolt) failures and PTO winch line failures began to occur, although the device remained capable of providing sufficient power to the installed UW AMP/WiBotic charging systems for approximately 3.5 months, until late January 2019.

Some of the lessons learned from the Hardware Reliability Surveys were incorporated into Task 6.2, which entailed development of alternate mooring designs.

Reports and Publications

Sea Engineering, Inc. March 2017. Task 7E: WETS Deepwater Mooring Inspection Report.

Sea Engineering, Inc., June 2017. Annual Report of the Wave Energy Test Site (WETS) at MCBH, Kaneohe 2016, (comprehensive report across several tasks).

TASK 6: SUPPORTING STUDIES

Under a contract modification in September 2012, supporting studies were implemented to expand and continue certain work. The output from wave arrays (wave farms) was modeled and used to refine earlier linear models used to estimate ocean area requirements and array overall capacity factor. A study was conducted to determine the feasibility of an improved and cost effective alternative to the conservative mooring design implemented at WETS. In addition, corrosion tests ongoing at the Heat Exchangers Test Facility at NELHA were continued to augment the database and identify low-cost aluminum alloys for use for WEC devices operating in the corrosive marine environment.

6.1 Operational Models for WEC Arrays

A WEC array model was required to evaluate combined output as a function of device spacing and optimized ocean area requirements, and to investigate interaction effects in large arrays of WECs. This is necessary for future commercial arrays as well as for the regulatory permitting process. Because WEC types are very diverse, (e.g., in their dimensions and principles of operation), two different approaches were followed to illustrate potential interferences among individual machines using robust analytical and numerical tools.

One study consisted of a theoretical determination of wave power extraction by arbitrary configurations of non-diffracting oscillating water column (OWC) WECs. In the simplified framework where OWCs are modeled as structureless pressure patches on the ocean surface, a mathematical solution for the overall potential flow from any wave farm was derived. Air compressibility in the OWC air chamber was included in the linearized equations. Wave spectral input typical of a particular site’s wave climate was used, in terms of significant wave height and wave power. Switching from the linear frequency domain to the time domain, turbine efficiency, which is a significant non-causal nonlinear effect, could be represented. Hence, both pneumatic and mechanical turbine power could be evaluated. The algorithm was demonstrated for large arrays in various rectangular and circular configurations for which the effect of WEC separation on overall power output could be assessed at two typical sites in Hawaiian waters. Results indicate the need for separation on the order of 3 to 5 OWC diameters, depending on array orientation, to limit interaction power losses to about 10%. Results are detailed in a journal publication, “Wave power extraction by arbitrary arrays of non-diffracting oscillating water columns” listed in the Reports and Publications below.

Another study considered very different WECs. The widely used potential flow software WAMIT™ was set up to analyze the hydrodynamic response of multiple slender articulated rafts consisting of floating cylindrical hinged segments. These machines were modeled to represent the well-known Pelamis® P1-750 WEC developed in Scotland, although the PTO adopted here was simply linear. The provision for hinge modes of motion already exists in WAMIT™ and proved quite useful. It was extended to the case of multiple hinged bodies. The PTO acts on relative rotational motions at the hinges, while external damping in the software is allowed in the form of resistive vertical forces only. Hence, the establishment of a dynamic equivalence between the two representations was necessary. The linear analysis of the machines’ PTO mechanism also required an interpretation of output once rated power (dictated by the choice of an electrical generator) was achieved in given sea conditions. Ultimately, the industrial developer’s recommendation to separate rows of such machines by half a length (75 m) and set the WECs a length apart (150 m) in any given row could be evaluated. Configurations were identified where more power could be produced than with the recommended spacing. These covered a significantly greater area, however, for power gains deemed marginal. Results are detailed in a document written by M. Frederick in partial fulfillment of the requirements for the M.S. degree in the Department of Ocean Resources Engineering at UH.

The outcome of Task 6.1 demonstrates that robust and generally available methods with modest computational needs may allow the estimation of WEC array performance. They also highlight the need to cast the issue of WEC interference in a greater context, since power output gains achieved at the expense of greater wave farm footprints are inherently problematic. From an infrastructural viewpoint, the costs of spreading WECs in space may be significant due to additional anchoring and power transmission constraints. Moreover, complex and potentially contentious permitting issues are likely to be exacerbated with larger wave farm footprints.

Reports and Publications

Journal Publications

Nihous, G.C., September 2012, Wave power extraction by arbitrary arrays of non-diffracting oscillating water columns, Ocean Engineering 51, 94–105, doi.org/10.1016/j.oceaneng.2012.05.016.v

Master’s Thesis

M. Frederick, April 2014, Hydrodynamic Modeling of Pelamis® P1-750 Wave Energy Converters using WAMIT™ software, (a plan B paper submitted in partial fulfillment of the requirements for the degree of) Master of Science in Ocean and Resources Engineering, University of Hawaii.

6.2 Alternate Mooring Designs

This task arose from results of at-sea tests of WEC devices at WETS. Under a contract modification in September 2012, supporting studies were implemented to expand and continue certain work, including a mooring design study. This study determined the feasibility of an improved and cost effective alternative design to the original mooring design used at WETS. The performance of the mooring systems for the three berths was first assessed, using information gathered under Tasks 4.4 and 5.2.3. The mooring designs were evaluated and modifications identified that led to less expensive, more effective designs for future use. Significant design and operational lessons were learned, and are summarized below.

By 2018, every mooring system used at WETS had required adjustments after initial installation, or failed completely. Ultimately, after failures on two legs of the 80m berth, in which chain joining links had failed in the dynamic zone of the catenary systems (where the chain interacts with the seabed), NAVFAC charged HNEI with redesigning and reinstalling significant portions of these systems. The 60m and 80m berths were redesigned, with the help of critical numerical design work by DNV GL. While this work was Navy-funded, it stemmed directly from insights gained during the years of monitoring and studying designs under HINMREC auspices. In May and June 2019, repairs were conducted on the 60m berth, including a pull-test and installation of a pretensioning “no-WEC hawser” system, in preparation for the anticipated deployment of the Ocean Energy OE35 WEC (which was subsequently delayed until likely the spring of 2021). Repairs at the 80m berth are planned for spring 2021, in advance of planned deployments at that berth.

The details of the mooring redesign can be found in reports done for the Navy by HNEI. These have been provided to DOE and can be made available to others upon request. In summary, the redesign included an increase of chain size in the chain risers (from the seabed to the surface floats) from 2-¾” to 4” chain, removal of 3 of the 5 sinker weights from each mooring leg (several of these had been destroyed by chain action during untensioned (no WEC) conditions), removal of “Kenter joining links” (not suitable for dynamic offshore applications), replacement of Kenters with heavy D-shackles, and replacement of surface floats with strengthened and fatigue-engineered strength members. Finally, the new mooring design includes the no-WEC hawser system mentioned above, keeping the mooring in a prescribed level of tension when a WEC is not installed. The lack of such a system in the initial design done for the Navy (by an outside contractor, prior to HINMREC's involvement) was determined to be a major factor in the ultimate failure of the two mooring legs at 80m, and eventually of one of the mooring legs at 60m (which occurred shortly before the repair was conducted).

It is highly recommended that the mooring systems proposed by all future tenants be evaluated by a third party. Under the HINMREC program, third party services were secured from DNV GL to evaluate the design of the 60m and 80m berths. This involvement led, in turn, to DNV GL being included in the design team for the mooring repairs completed at the 60m and 80m berths.

The primary mooring work was completed between 10 and 15 May 2015, with the mooring itself installed, on each of three mooring legs, including new surface floats and chain down to a point on the seabed where the new chain was connected to the existing ground chain. The revised design uses a larger diameter chain to address fatigue issues, as well as the no-WEC hawser system to keep the mooring in tension and reduce fatigue and wear. Following weather interruptions, a pull test to 100T was executed on 8 June, and the no-WEC hawser system was installed on 22 June. A similar effort will be conducted at the 80m berth in 2021 under Navy funding.

Some Related Lessons Learned for WEC Deployment Planning at WETS, or Elsewhere

Important design and operational lessons learned that are applicable elsewhere can be summarized as follows:

- Design of WEC systems and moorings should consider the capabilities of vessels of opportunity available at the deployment site.
  - As a budding industry, current and proposed future WEC sites in the U.S. are not necessarily situated in areas where offshore services are readily available. Therefore, there may be limitations on heavy lift, dynamic positioning, and heave compensated lift vessels. While these types of equipment can be mobilized to a site from afar, the mobilization costs are generally prohibitive and detrimental to a project.
  - WEC device developers should work with local marine contractors to determine the types of offshore capabilities that are available readily and consistently. Whenever possible, developers should integrate local marine resources into the design process at an early stage. This step will reduce future installation and maintenance costs for the device while it is in place.

- Access points and ease of maintenance and servicing of WEC devices are important design considerations.
  - WEC device developers face a tradeoff between making WEC devices easy to access and service for marine contractors, and preventing unwanted trespassing by the public. In Hawaii, WETS is located in a controlled area of MCBH waters and, therefore, has not

experienced trespassing or vandalism to devices or components. It is critically important for safety and ease of maintenance that boarding and access for vessels and crew is taken into consideration during design of the system.

  - When concerns of vandalism and trespassing are great, design consideration should be given to integrating temporary boarding solutions that can be brought out and installed during periods of servicing.

- Mooring systems should be an integral part of overall WEC device design.
  - A WEC device will only be as successful as its mooring system. WEC device designs vary, and associated mooring tension and slack also vary according to what the developers need to maximize performance of their device. Improper selection of mooring components, or application of components, can lead to unforeseen failures, downtime and repairs not directly associated with the device.
  - A successful mooring design system will lead to less downtime of the device and greater energy production.

- Under Navy funds, ARL-UH has conducted extensive mooring analysis associated with both the deep berth mooring repairs and the mooring of Lifesaver at the 30m berth. This mooring analysis capability, begun under HINMREC funding, has become a key aspect of support to the Navy and to the developers deploying at WETS, whether Navy or DOE funded. Primarily, ANSYS AQWA hydrodynamics simulation and diffraction software is used for this analysis.
  - A substantial body of knowledge has been built up by HINMREC during this process. The deep berth moorings at WETS have been substantially redesigned, primarily in collaboration with DNV GL, as a subcontractor to design lead Sound and Sea Technology. The new mooring design, taking both strength and fatigue into consideration, is detailed in reporting to Navy, and can be shared with DOE, and potential WEC developers deploying at WETS, on request. It is deemed absolutely essential that very careful mooring analysis be a part of any WEC deployment, and third-party mooring analysis should be a key component of DOE approvals of WEC deployments at the new PacWave test site in Oregon, or at WETS.

Reports and Publications

Technical Reports

DNVGL, Noble Denton Marine Services, September 2017. Evaluation of WETS Mooring; Failure Mode Investigation Report, prepared for Sea Engineering Inc.

Conference Presentations

Rajagopalan, K., Cross, P., Vega, L., April 2018. Numerical modeling of the lifesaver mooring system for deployment at WETS, METS (Marine Energy Technology Symposium), Washington DC.

6.3 Aluminum Corrosion and Biocorrosion Studies

Corrosion studies began with investigation of aluminum corrosion in the splash-spray zone, surface waters, and deep ocean water for OTEC and WETS device applications. Components were identified and standard sample coupons with and without coatings were tested. The exposed samples were analyzed in the Hawaii Corrosion Laboratory (HCL) at UH to determine corrosion mechanisms. A novel corrosion-resistant ceramic-polymer hybrid coating developed at HCL was examined. In addition, corrosion at the field sites was investigated with a portable exposure corrosion rack mounted on the Army Logistic Support Vessel in Pearl Harbor.

Biofouling and biocorrosion studies of sample coupons – on actual wave power devices and OTEC components – was conducted using molecular methods to identify the composition of fouling communities. Innovative marine coatings, containing natural compounds extracted from algae and sponges and conductive polymers, were tested in the laboratory to determine if they are effective in providing protection from biocorrosion to ferrous and non-ferrous metals. Al-6061 and Al-5083 coupons were treated with different anti-fouling coatings, and subsequently immersion tested at the Makai Research Pier on the windward side of Oahu.

Aluminum corrosion and biocorrosion testing was also conducted at the OTEC Heat Exchangers (HXs) Test Facility, located at the Natural Energy Laboratory of Hawaii Authority (NELHA), in Kona on Hawaii Island. In 2012, corrosion work at HCL and Makai Pier were discontinued due to NEPA Compliance issues, and results incorporated into NELHA efforts.

HINMREC contracted with Makai Ocean Engineering to develop a corrosion test method to measure the primary corrosion mechanisms of concern - surface pitting and crevice corrosion. The overall objective was to develop a method of measuring the growth rates of corrosion pits in aluminum for the purpose of determining the operating life of an OTEC heat exchanger. Testing and development were conducted at Makai's corrosion and heat exchanger test facility at NELHA.

Makai developed a system to observe pit growth in-situ using optical imaging and ultrasonic thickness measurements, which allow corrosion development to be monitored over time without the removal and destruction of samples. Three aluminum alloys were chosen for testing (Al 2024, Al 6061-T651 and Al 5086-H116) in flowing (1 m/s) and near-stagnant cold, deep seawater (6 samples total). In all corroding samples, the ultrasonic scans revealed crevice corrosion progressing underneath the gasket interface. The largest amount of gasket corrosion occurred in the near-stagnant water conditions. Maximum pit depths of 0.8 mm underneath the gasket and lateral penetrations of 6 mm from the inside edge of the gasket have been observed. For Al 5086 and Al 6061, a significant change in open circuit potential (measured against an Ag/AgCl reference electrode) was observed at the onset of corrosion. Implications of aluminum corrosion on OTEC heat exchangers and techniques to implement corrosion monitoring in an OTEC plant are discussed in the final report ("Makai Engineering, January 2015. OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring, Final Report." listed in Reports and Publications below).

Based on this long-term aluminum corrosion and biocorrosion testing on OTEC components, it was determined that certain cost effective alloys can be used in OTEC heat exchangers:

- Evaporators: Alloys 3003; 5052; and, 6063-T5 can achieve projected life expectancy of 30-years
- Condensers: Alloys 3003 and 5052 can achieve projected life expectancy of 30-years but 6063-T5 did not qualify

The OTEC HX Test Facility continues to be maintained operational by Makai Ocean Engineering under ONR contracts from HNEI.

Reports and Publications

Technical Reports

Hihara, L.H., Kusada, K., September 2011. Corrosion of Bare and Coated Al 5052-H3 and Al 6061-T6 in Seawater, Progress Report.

Makai Engineering, May 2012. Aluminum Pitting Corrosion Measurement Methods, Progress Report #1.

Makai Engineering, July 2012. OTEC Heat Exchanger Program: Progress Report #2.

Makai Engineering, June 2013. OTEC Heat Exchanger Program: Progress Report #3, (corrosion apparatus).

Makai Engineering, August 2013. OTEC Heat Exchanger Program: Progress Report #4 (test procedure).

Makai Engineering, September 2013. OTEC Heat Exchanger Program: Progress Report #4, (MA140003).

Makai Engineering, October 2013. OTEC Heat Exchanger Program: Progress Report #5.

Makai Engineering, October 2013. OTEC Heat Exchanger Program: Annual Report (photographic imaging, ultrasonic inspection, and laser profilometry).

Makai Engineering, May 2014. OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring, Task 4, Status Report #1.

Makai Engineering, September 2014. OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring, Status Report #4, (MA140003).

Makai Engineering, January 2015. OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring, Final Report.

Makai Engineering, February 2015. OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring, Final Report, (MA140003).

Makai Engineering, April 2015. Task 2, OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring, Rack Construction and Status, (Subaward MA1500177).

Makai Engineering, November 2015. OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring; Shakedown Test, (Revised).

Makai Engineering, January 2016. OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring; Status Report #1, (MA150017).

Makai Engineering, March 2016. OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring; Status Report #2, (MA150017).

Makai Engineering, August 2016. Task 6, OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring; Status Report #3, (MA150017).

Makai Engineering, August 2016. OTEC Heat Exchanger Program: Ultrasonic Scanning for Corrosion Monitoring, Final Report, (MA150017).

L.H. Hihara, and K. Kusada, September 2017. Corrosion of Bare and Coated Al 5052-H3 and Al 6061-T6 in Seawater.