

Hawaii Renewable Energy Development Venture Technology Assessment Wave Energy

1. Overview - Issues and Enabling Technology Needs

The state of Hawaii has a general coastline of over 1200 km, the fourth longest in the U.S., and an exclusive economic zone (EEZ) of about 2.4 million km². Previous studies have confirmed that Hawaii enjoys a superior wave energy resource and is, therefore, an excellent candidate market entry point for large-scale hydrokinetic energy conversion technologies. Wave systems have the potential to supply electrical power far in excess of current demand on all islands except Oahu, where about 75% of the state's population resides (SEASUN Power Systems, 1992). Even on Oahu, harnessing the wave resources off the north shore could meet almost two-thirds of the island's electricity demand. See Figure 1.

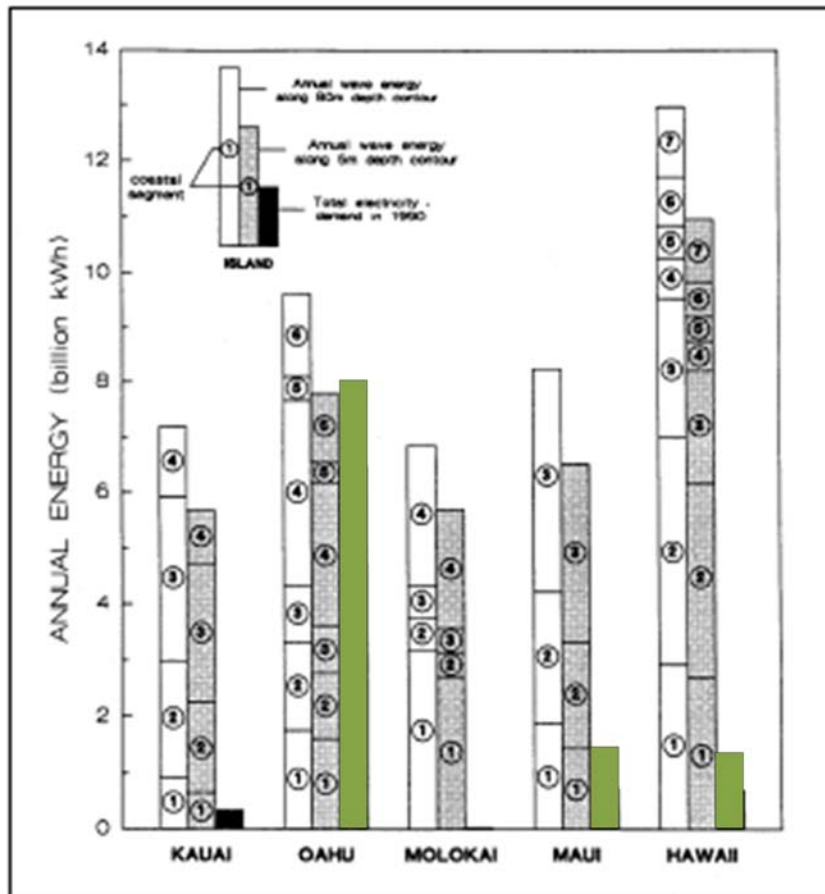


Figure 1: Annual wave energy resource compared with annual electricity demand updated to 2007¹²

¹ Hagerman, George. 1992. "Wave Energy resource and economic Assessment for the State of Hawaii," Prepared by SEASUN Power Systems for the Department of Business, Economic Development, and Tourism, Final Report, June 1992. The report

Most of Hawaii's wave energy resource is produced by the northeasterly Trade Winds that blow throughout the year. These winds have monthly average velocities between 5 to 8 m/s and generate waves with a dominant period of 6-8 s and significant heights of 1-2 m. Smaller contributions to the resource come from long swells resulting from distant storms. Along coastlines with a northeastern exposure, the average wave power density along the 80 m depth contour lies between 10-15 kW/m, dropping by about 20%, due to refraction and shoaling, by the time the 5 m depth contour is reached (SEASUN Power Systems, 1992). At these power densities, the electricity demand of the counties of Hawaii, Maui, and Kauai could be satisfied by recovering a small percentage of the wave energy resource available on the outer shelf of the north coasts of these islands.

The isolation and relatively low installed generating capacities of the power grids on the various islands (about 1700 MWe for Oahu; 290 MWe for the county of Hawaii; 280 MWe for Maui; and 90 MWe for Kauai) present a unique challenge with respect to stability problems that can arise when conventional units that provide grid support are displaced by wave power. The utility on the island of Hawaii has been attempting to address these stability and reliability issues caused by a sharp increase in wind-generated power added to its grid over the past year. Experience gained from the grid-integration of wave power systems in Hawaii would particularly benefit the application of such technologies in other isolated communities and their export to small rural markets in the developing world.

As illustrated in Figure 1, all islands except Oahu, could meet their total electricity demand in 2007 with wave energy.

has been updated for 2007 for HECO, MECO, and HELCO shown in green.

² Hawaiian Electric Company 2007 Corporate Sustainability Report.

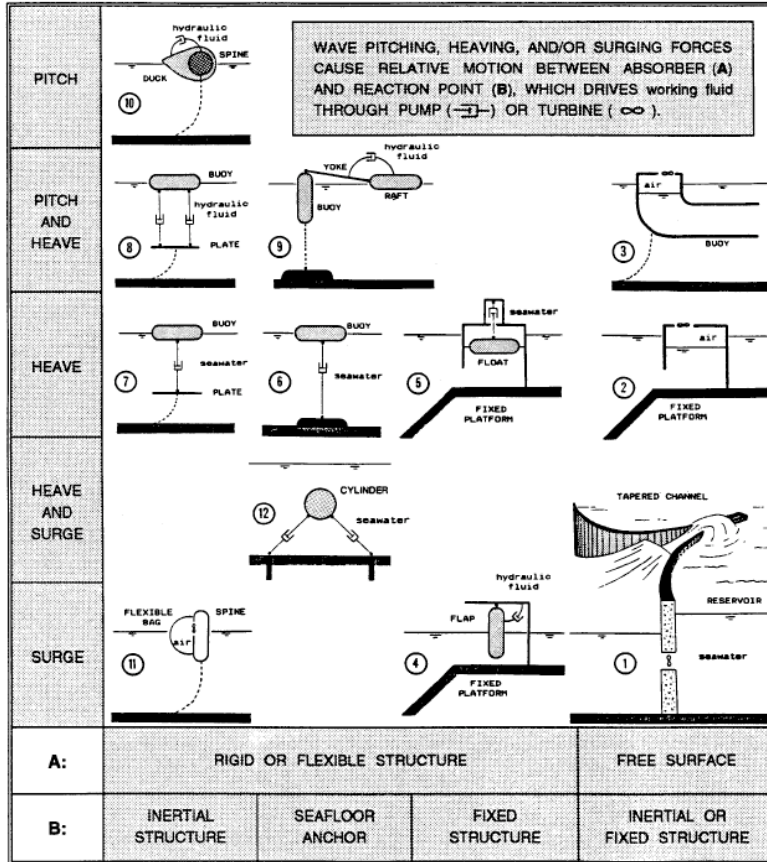


Figure 2: Wave Energy Conversion Processes

A wide variety of technologies are being developed to capture the mechanical energy contained in the surface-level wave action and below surface pressure fluctuations associated with ocean waves. Working together, private companies and government bodies have developed several forms of wave energy converters, including both onshore and offshore systems. Onshore wave technologies rely on the energy contained within breaking waves while offshore technologies make use of open ocean wave action. Several examples of onshore and offshore systems are presented in Figure 2.

2. Status of Commercial Readiness

While there are many different wave energy systems under development, there are no known commercial systems currently deployed. The following describes several types of technology under development.

Fixed Wave Energy Technology

Fixed (unmoving, generally onshore) wave energy technologies include the oscillating water column and tapered channel (tapchan).

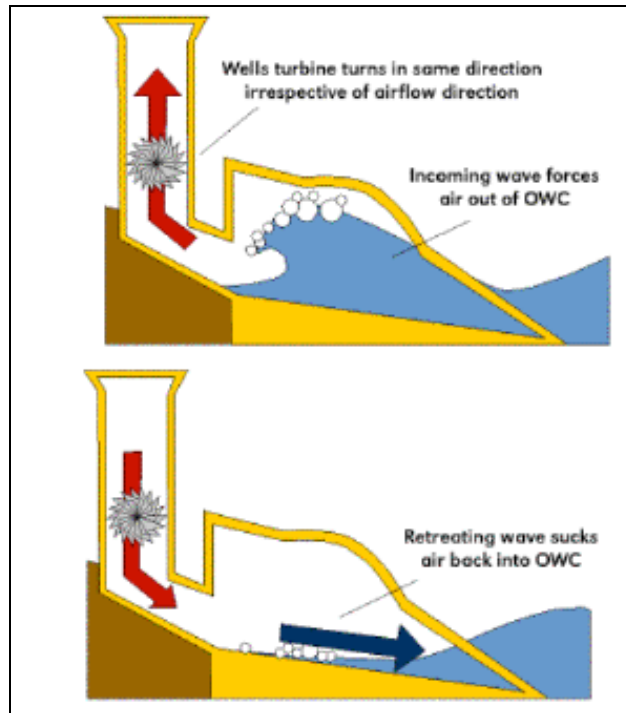


Figure 3. Conceptual diagram of oscillating water column technology³

- Oscillating water column:** The most well-studied and developed wave energy technology, the oscillating water column is a partially submerged structure made of steel or concrete. The open-ended bottom of the oscillating water column is fully submerged below the waterline, and encloses a column of air above a column of water.⁴ As the water column rises and falls due to waves entering the air column, the air column compresses and depressurizes; as the wave retreats, the pressure draws air back through the turbine. The movement of air within the column spins a turbine that in turn powers a generator to produce electricity.

Significant infrastructure requirements and environmental conditions are necessary for an oscillating water column system. Built along the shoreline, construction demands a “dry” site, a condition generally achieved through the use of a costly barrier wall protecting the site

³ Research Institute for Sustainable Energy (RISE), “Wave Resources”, Accessed: August 2007, Available: <http://www.rise.org.au/info/Res/wave/index.html>

⁴ U.S. Department of Energy, Energy Efficiency and Renewable Energy, “Ocean Wave Power” available http://eee.eere.energy.gov/consumer/renewable_energy/ocean/index.cfm/mytopic=5009.

from incoming ocean water.⁵ The ideal locations for siting oscillating water columns are often inaccessible by heavy equipment or conflict with zoning or environmental protection measures. Since 2000, a 500 kW ocean energy system that makes use of oscillating water column technology has been operating on the island of Islay, Scotland and successfully produces power for the national grid.

- **Tapered Channel (Tapchan):** A tapchan is an ocean-facing concrete structure built into the side of a cliff. The water enters at a slight grade into a wide mouth entrance that gradually tapers as it approaches the reservoir on land, causing the incoming waves to increase in height and spill over the concrete walls.^{6 7} Mimicking many hydroelectric power plants, the reservoir water feeds through a turbine that spins to produce electricity. A major benefit of the tapchan technology is its capacity to store electricity generated. Like the oscillating water column, tapchan systems are difficult to site. First, few coastal locations are suitable for this technology and promising locations may be off limits for zoning and/or environmental reasons.

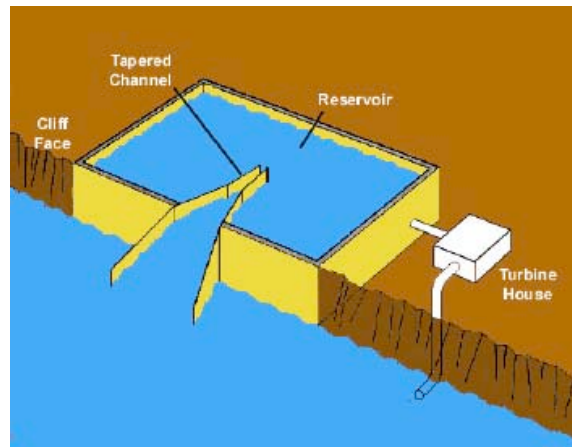


Figure 4: Conceptual diagram of tapchan technology

⁵ Kelly J. Kimball, "Embedded Shoreline Devices and Uses as Power Generation Sources", Oregon State University, 2003

⁶ Ibid

⁷ U.S. Department of Energy, Energy Efficiency and Renewable Energy, "Ocean Wave Power".

Offshore Wave Energy Technology

Two promising offshore technologies include the Pelamis Wave Energy Converter and Wave Dragon Wave Energy Converter.

Pelamis: The Pelamis Wave Energy Converter consists of cylindrical segments connected by hinged joints that mimic the movement of waves driving electrical generators to produce electricity. Seabed cables transfer power to shore and a single cable is capable of supporting the power input of several Pelamis devices. Each device has a maximum rated capacity of 0.75 MW. A Pelamis wave farm is envisioned to produce up to 30MW (at least 40 devices) over a square kilometer area.

It was the world's first commercial scale machine to generate electricity into the grid from offshore wave energy and the first to be used in a commercial wave farm project. The first full scale prototype was successfully installed and generated electricity to the UK grid at the European Marine Energy Center in Orkney, Scotland in August 2004. The first wave farm consisting of three Pelamis machines and located off the coast of Portugal, was officially opened in September 2008. The current recession as caused the Portugal project to be shut down. ⁸



Figure 5: Pelamis Wave Energy Converter (single device)

Wave Dragon: Developed in collaboration with six European nations, the Wave Dragon functions similarly to the tapchan apart from being moored in deep water as opposed to built into a cliff face. Overtopping waves enter

⁸ www.pelamiswave.com

the water holding area and are funneled through a turbine-generator system to produce electricity. A grid-connected 7 MW Wave Dragon system is planned for the coast of Wales with operation to begin in 2008. Benefits of the Wave Dragon include its use of mature, existing technologies, the capacity to scale up electricity production, and low operating and maintenance costs.⁹

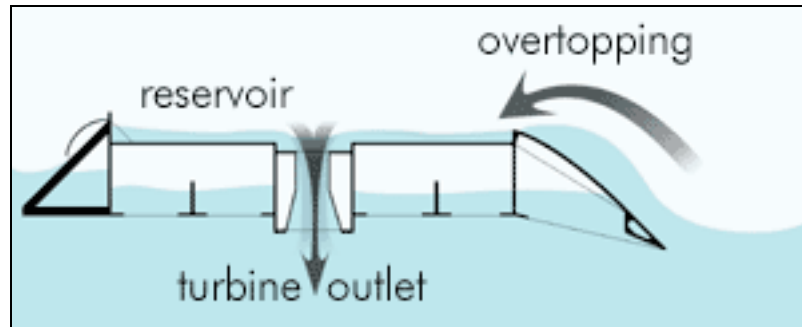


Figure 6: Wave Dragon Technology Principle



Figure 7: Wave Dragon Wave Energy Converter

Ocean Power Technologies (OPT): OPT's PowerBuoy® wave generation system uses a "smart," ocean-going buoy to capture and convert wave energy into low-cost, clean electricity. The rising and falling of the waves off shore causes the buoy to move freely up and down. The resultant mechanical stroking is converted via a sophisticated power take-off to drive an electrical generator. The generated power is transmitted ashore via an underwater power cable. A 10-Megawatt OPT power station would occupy only approximately 30 acres (0.125 square kilometers) of ocean space. An OPT 40 kW system is currently under test at the Kaneohe Marine Base on

⁹ <http://www.wavedragon.net>

Oahu.¹⁰



Figure 8: OPT PowerBuoy®

Oceanlinx: Oceanlinx’s core patented technology is an Oscillating Water Column (OWC) device, based on the established science of wave energy, but one which – when compared to other OWC technologies – offers major improvements in the design of the system, the turbine, and in construction technique. The technology has been successfully constructed and tested with the first full scale Oceanlinx wave plant, installed at Port Kembla in NSW, Australia. It is expected to have the lowest production cost per unit of its wave power peer group (source: Electric Power Research Institute).¹¹



Figure 9: Oceanlinx Technology

3. Appropriateness to Hawaii

National Marine Renewable Energy Center in Hawaii (“Center”)

Wave energy systems face many challenges that must be overcome before they are widely used. Among these challenges are:

- Visual impact;

¹⁰ <http://www.oceanpowertechnologies.com>

¹¹ <http://www.oceanlinx.com>

- Noise;
- Disturbance or destruction of marine life;
- Coastal erosion;
- Threat to navigation;
- Interference with commercial and sport fishing;
- Interference with other recreational activities;
- Location-dependent;
- Sited in marine environment;
- Maintenance requirements;
- Power transmission;
- Transmission capacity;
- Variable resource;
- Diffuse resource;
- Power quality;
- Penetration limits;
- Efficiency;
- Economics; and
- Stage of Development.¹²

In 2009, the Hawaii Natural Energy Institute (HNEI) of the School of Ocean and Earth Science and Technology (SOEST) of the University of Hawaii (UH) was awarded a 5-year contract by the US DOE to establish one of two National Marine Renewable Energy Centers. The Center will be a collaborative effort between academia, industry, government, and NGOs. Our partners include technology developers, the local electric utilities companies, a large engineering contracting company that can also provide financing opportunities for future commercialization efforts, and the State of Hawaii. International partners currently include groups from Norway, France, and the United Kingdom; additional partners from Asia are anticipated once the Center is established.

The primary objective of the Center is to facilitate the development and implementation of commercial wave energy systems for use in Hawaii and elsewhere in the world. For validation, the target is for one or more of these systems to be supplying power to the local grid at >50% availability before the end of the 5-year period of the Center's performance. The Center will assist in completing necessary environmental studies and help industrial partners acquire required permits. It will provide engineering support to developers and will work with industrial partners to monitor the performance of deployed systems. The Center will also coordinate information exchange among appropriate parties. Wave energy field test facilities developed under this program will offer opportunities for component optimization and testing of complete systems. National and international partnerships will be leveraged to assess the potential for the export of technologies to other

¹² "Feasibility of Developing Wave Power as a Renewable Energy Resource for Hawaii", January 2002, Department of Business, Economic Development, and Tourism.

markets.

The Center plans to achieve these objectives through: 1) partnerships it will promote between marine power system developers, utility companies, financing sources, engineering and environmental support companies, academia, local, state, and federal government agencies, and non-governmental organizations (NGO's); 2) the establishment of up to four field test facilities in the state of Hawaii for wave-power and OTEC systems; 3) the creation of a web-based virtual Center that will serve as a forum to facilitate the international exchange of information, test data, and modeling results; and 4) hosting annual meetings of Center participants and other stakeholders.

Industry will be the driving force behind the Center. While specific technical objectives and timelines will necessarily reflect the business plans of these businesses, the overall intent of the project is to accelerate the development of marine renewable energy technologies in general and to address the needs and concerns of the public. Furthermore, the Center will be structured and managed to provide, to the greatest extent possible, open access to its facilities and expertise, and broad dissemination of non-proprietary information, for all credible wave power system developers and other stakeholders. This policy will not be determined nor diminished by the commercial agendas of the founding industrial partners.

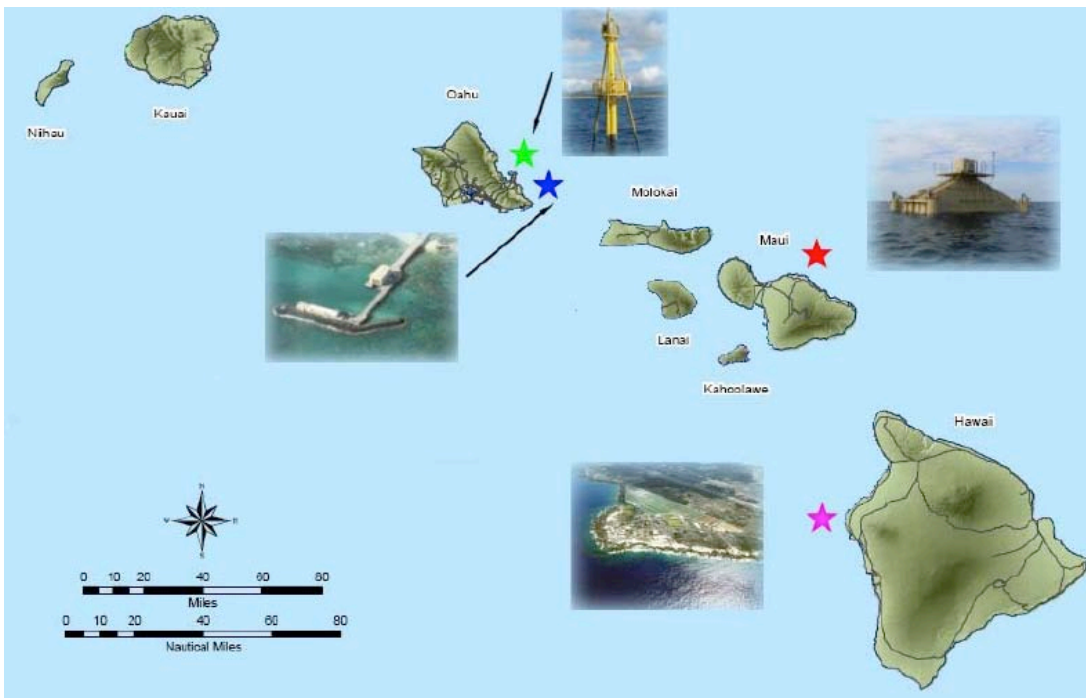


Figure 10. Locations of the four test facilities.

The locations of the four test sites are illustrated in Figure 10. The green star indicates the general location of the OPT project site offshore of the

Kaneohe Marine Corps Base Hawaii; the OPT buoy is shown in the adjacent picture. The blue star is the location of the Makai Research Pier seen in the aerial photo. The red star is the planned site of the Oceanlinx oscillating water column device shown in the photo. NELHA on the west coast of the island of Hawaii is being considered as an OTEC component test site.

Two wave energy projects have been initiated that may soon be delivering electricity to the power grids on Maui and Oahu. In February 2008, Oceanlinx, Ltd. of Australia in collaboration with Maui Electric Company (MECO) announced plans to provide up to 2.7 MWe from two or three floating platforms located about 1 km offshore of Pauwela Point on the northeast coast of Maui. Power will be generated using Oceanlinx's oscillating water column technology that has been tested previously at a facility in Port Kembla, NSW, Australia. Oceanlinx also is developing wave energy systems in Victoria, Australia; Cornwall, U.K.; Namibia; and Rhode Island. The \$20 million privately-funded Maui venture may be operational by the end of 2009. Oceanlinx currently is negotiating a power purchase agreement with MECO who will be seeking approval for this agreement from the Hawaii Public Utilities Commission (PUC) and who will provide the necessary transmission and interconnect infrastructure. MECO, Oceanlinx, and Planning Solution, Inc., a private environmental consulting firm located in Honolulu that has been engaged to prepare the EIS by Oceanlinx, are partnering with UH on the Hawaii National Marine Renewable Energy Center. MECO intends to provide substantial cost share, and the Pauwela Point site on Maui will be one of the field test locations operated by the Center. Center investment at this site would leverage and expand the Oceanlinx permitting efforts and in the later years, leverage the undersea power and instrumentation cabling provided by MECO. This would allow testing by other power providers. The Center would also conduct testing and obtain oceanographic data that would benefit wave power system development.

At a second site offshore of the Kaneohe Marine Corps Base Hawaii (KMCBH) on the windward (northeast) coast of the island of Oahu, Ocean Power Technologies (OPT) has been testing a single 40 kWe buoy in 30 m depth water. The up and down motion of the buoy is used to drive a generator which is connected to shore via an undersea cable. Commercial scale applications will require arrays of buoys. OPT has been collecting data since the first unit was deployed in June 2004 and has completed an extensive EA. This project, funded by the Office of Naval Research (ONR), is intended to demonstrate the feasibility of wave power for naval facilities worldwide. OPT also has projects in New Jersey and Spain.

Center Scientific Research Areas

Brief descriptions of research that will be performed over the 5-year period of the initial contract are provided below. The results of this research will be great value to industry.

- ***Perform research on advanced wave forecasting technologies.*** The key objective of the research to be performed is to identify time windows and locations around the Hawaiian Islands that are most favorable for the operation of wave power systems and, in so doing, to identify and develop effective forecasting protocols and methods. This work will be led by participating faculty from the Departments of Ocean and Resources Engineering (ORE) and Oceanography (OCE). ORE has been operating a model system to provide 7.5-day experimental forecasts of wave conditions around the Hawaiian Islands at regional and island scales. The system includes the spectral wave models WaveWatch3 (WW3) and Simulation Wave Nearshore (SWAN) as well as the Coastal and Estuarine Circulation (ECOM) model. These models provide forecast runs every 6 hours for the Hawaiian Islands from Niihau to Hawaii at 6-km resolution and the individual islands at 600-m resolution. In each forecast run, the NOAA Global WaveWatch3 model and TPXO.6 global tidal database provide the wave and tide boundary conditions. The high-resolution atmospheric models (MM5/WRF) with proper depiction of terrain and land surface conditions operated by the UH Department of Meteorology provide the wind forcing that accounts for the modification of large-scale flow by the Hawaiian Islands with heights ranging from 500 to 4100 m.

It is planned to improve the accuracy of the wave forecast and to use the resulting system in hindcast mode to develop a wave atlas of the Hawaiian Islands. Improved wave forecasting accuracy will aid the deployment and operation of test devices, while the wave atlas will offer detailed information about the wave energy resource that will be of significant value for planning future commercial wave power systems and for related environmental studies. A key component of the proposed work is to enhance the Hawaii regional MM5/WRF, which provides the wind forcing to the spectral wave models, by assimilating satellite observations of ocean surface winds into the regional atmospheric model. Both WW3 and SWAN consider wave propagation, refraction, shoaling, and breaking under the influence of specified wind and current fields. Addition of diffraction will greatly enhance the spectral wave models in describing the wave conditions on the leeward side of islands. This enhanced model package provides a good opportunity to create a wave database for the Hawaiian Islands with high-resolution simulated winds diagnosed from atmospheric models using NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research) reanalysis data for the past 5 years. The database allows better understanding of the seasonal wave climate around the Hawaiian Islands.

- ***Conduct experimental and numerical modeling for optimization of marine energy conversion devices and arrays.*** Faculty from the UH College of Engineering and SOEST will support the field testing as appropriate but will also undertake complementary laboratory studies and numerical modeling directed toward a wider range of applications. Two primary objectives will be pursued that relate to wave power systems: 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 of prototype devices being investigated at the Center's field sites. Objective 2 will also involve improvements of laboratory facilities and protocols and will provide data to calibrate and validate the numerical simulation packages.

ORE and HNEI personnel have developed codes to analyze wave-structure interactions (e.g., OTEC pipeline towing). Laboratory experiments will leverage existing facilities at the UH Department of Civil and Environmental Engineering including a 15.2 m (l) x 1.2 m (w) x 0.9 m (d) wave tank/wave generator equipped with a towing carriage. A longer 1.8 m deep wave flume and towing carriage is being constructed with funding from ONR, the UH College of Engineering, and the Hawaii Department of Transportation. This facility will also be available for the wave energy experiments. The new wave flume will have 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, as well as a self-circulation system that can produce currents up to 1 m/sec. Instrumentation include multiple wave gauges and data acquisition systems, a 3-D Laser Doppler Velocimeter (LDV) and a 3-D Particle Image Velocimeter (PIV), video cameras, high speed cameras, and flow meters.

Experiments will be conducted under different wave conditions and will examine single devices and series of devices arranged in different patterns. An additional area of interest is the use of manmade wave focusing structures to enhance the performance of wave power devices. Previous research has determined that water waves can be focused to increase their amplitude by propagation over a submerged structure. In this project, we will conduct laboratory experiments to explore the possibility of developing practical wave focusing lenses that can be deployed with various wave power devices in the ocean.

• ***Identify opportunities for cross-fertilization and development of economies of scale between other renewable sources and marine and hydrokinetic renewable energy sources.*** Most renewable energy systems, including wave power, generate power intermittently, i.e., only when the resource is available. From the utility perspective, the inability to plan ahead with confidence makes economic dispatch of generating units difficult. If such intermittency occurs over a short time frame, then spinning and/or regulating reserve is necessary to ensure stability, further reducing the economic dispatch of the other generating units. In the extreme, such as with wind which can exhibit very significant short-period fluctuations, intermittency can lead to power quality issues that often results in the utility shedding the renewable energy generator from the grid system. While wave energy systems are expected to be more predictable and less transient than wind systems, there have not been, to our knowledge, any detailed

assessments of the integration of large scale ocean energy systems into the grid.

Under funding from the Department of Energy, HNEI, in partnership with GE Global Research Center (GE GRC) and the local utility companies, is developing detailed dispatch and dynamic models for the various Hawaiian Islands. These models, based on the GE GRC MAPS (dispatch) and PSLF (dynamic) models, are able to accurately evaluate the effect of intermittent energy sources on system stability and power quality.

With their small and isolated grid systems and relatively high penetration of renewables including wind, geothermal, and biomass, the islands of Hawaii and Maui are excellent case studies to apply these validated models to investigate the effect of linking ocean energy systems with other renewable energy systems. By integrating wave power performance data from the planned field tests with high fidelity grid models and advanced wave forecasting techniques, we will be able to assess the value of grid-connected wave power facilities.

A considerable amount of work is being undertaken to model the behavior of mixed portfolios of conventional and renewable power systems on Maui and the island of Hawaii. Ongoing modeling activities being led by HNEI are focusing on identifying technology systems or operating strategies (e.g., energy storage; advanced forecasting) that can respond to rapid grid frequency fluctuations caused by variations in wind turbine output. We intend to incorporate wave energy technologies into this analysis. This study will help the utility to properly site and size storage devices, address issues related to the interconnection of wave energy systems and the reliability of wave forecasting techniques, and provide comparative operational characteristics of different wave energy technologies.

Wave power could provide additional electricity to the Oahu grid without disrupting stability and could be linked to the new biodiesel systems. A grid modeling effort by HNEI for Oahu is planned to start by the end of 2008 and could incorporate the Kaneohe OPT facility.

Testing ocean power systems on three different islands, each with unique grid characteristics, allows an evaluation of the operation of these technologies under different energy regimes. The proposed grid modeling will provide vital information to facilitate the successful integration of these power systems into a range of potential markets with different stability considerations.

• ***Study the compatibility of marine and hydrokinetic technologies and systems with the environment, fisheries and other marine resources.*** This study will include three components: 1) evaluation of chemical and biogeochemical threats posed by various discharges associated with wave energy devices; 2) a general assessment of the impacts of ocean energy

installations on marine life; and 3) the effects of OTEC sea water removal and discharge on the food web and the potential for degradation of the thermal resource. These issues can profoundly influence the permitting process and commercialization of marine renewable energy conversion technologies. The study will be conducted by faculty from OCE, HNEI, and the International Pacific Research Center (IPRC) of SOEST.

Chemical and biogeochemical impacts of OTEC operations have been studied previously (e.g., Sansone & Kearney, 1984, 1985; Sansone & Smith, 1986; Quinby-Hunt *et al.*, 1986). Potential impacts of non-OTEC marine renewable energy systems such as hydrokinetic devices are less understood, particularly with respect to tropical and island environments. Possible chemical and biogeochemical environmental effects may include: release of anti-biofouling agents; disposal of removed biofouling; lubricants and surfactants released during operations and inadvertent spills; nutrient-rich groundwater released from electrical-cable shore crossings; and particulate matter released during the installation of moorings and shore crossings. As a specific test case, the Oceanlinx wave power facility planned for deployment off Maui will be analyzed to determine and rank the significance of these possible effects and to assess the sensitivity of the specific site to these effects. Methods to eliminate or mitigate significant impacts will be explored. This study will serve as a template for similar assessments of other types of wave power devices.

On the second topic, different types of ocean energy installations (e.g., buoy arrays; floating platforms; OTEC suspended pipelines) will be analyzed to identify the full spectrum of possible impacts on marine animals. For example, objects placed in the ocean frequently attract and aggregate fish, sharks and other organisms. Installations may cause entanglement of whales, seals, turtles, birds and other animals or may be used as haul-outs and resting sites by seals and birds. The noises created by ocean installations can alter the acoustic environment and impact whales and other acoustically sensitive animals. Electromagnetic signatures of ocean energy installations may be picked up by animals that use such signals for navigation and positioning. Migration routes and timing can be altered as a result. In order to understand, predict, and mitigate the impacts of ocean energy installations on animals, it is necessary to understand whether they will be attracted, repelled or unaffected by a particular device, and to evaluate how different designs affect these responses. Siting decisions must also consider how specific areas are used by different species. Since the literature contains a significant body of information on animal responses to marine structures and anthropogenic disturbances, this study will apply these results in its analyses. Additional information will be collected during the field tests.

• ***Increased reliability and survivability of marine and hydrokinetic renewable energy technologies, including development of corrosive-resistant materials.*** The research on this topic will focus on corrosion. The

viability of ocean power generating technologies will be affected by their ability to resist corrosion in the harsh marine environment. General corrosion, pitting, crevice corrosion, and galvanic corrosion may occur depending on various factors. In addition to the ubiquitous chloride ion, sulfuric acid exposure by the reaction between sulfur dioxide and water is a growing concern in Hawaii due to emissions from the Kilauea volcano that have recently increased approximately five fold from a normal output of 150 - 200 metric tonnes/day. Above-water structures are subject to aggressive attack when exposed to volcanic smog that can be advected across the entire state by occasional southeasterly winds. Conventional marine corrosion data found in the literature may underestimate the speed and extent of material degradation in the Hawaiian environment.

Marine installations also are vulnerable to biocorrosion which is a serious problem for power generation facilities and the offshore oil and gas industry (Scotto *et al.*, 1986; Acuna *et al.*, 2006; Bermont-Bouis *et al.*, 2007). Microbial-influenced corrosion (MIC) alone accounts for 20-30% of all corrosion losses (about \$30-50 billions per year). Biocorrosion occurs when complex microbial consortia interact with metallic surfaces through the establishment of multispecies biofilms (Fenchel, 2002). Biofilms mediate interactions between metal surfaces and the liquid environment, leading to major modifications of the metal-solution interface by drastically changing the types and concentrations of ions, pH, and oxygen levels. The mechanism of biocorrosion is complex and insufficiently understood (Videla and Herrera, 2005). While application of biocides and surfactants has been successful in mitigating biocorrosion (Lechavallier *et al.*, 1988; Al-Darbi *et al.*, 2002; Tsai *et al.*, 2003; Aleman *et al.*, 2006), effects are generally temporary and may not be acceptable for use in sensitive marine habitats.

The corrosion studies that will be undertaken will leverage facilities at the Hawaii Corrosion Laboratory (HCL) at UH. HCL was established with \$8 million of funding provided by the U.S. Army Corrosion Office since 2003 for its Pacific Rim Corrosion Research Program and Pacific Rim Environmental Degradation of Materials Research Program. HCL has established eight atmospheric test sites (including two in marine settings) at different locations in Hawaii that take advantage of the state's diverse micro-climates and environments (Hihara *et al.*, 2008). It also operates a state-of-the-art corrosion, electrochemistry, and materials characterization facility for investigating corrosion mechanisms and determining the relationship between microstructure and corrosion behavior. The HCL specializes in synthesizing hybrid ceramic-polymer (ceramer) coatings for corrosion protection. Several novel coatings have been developed for aluminum and zinc that have shown exceptional promise for use in marine environments.

Test facilities will be set up at the Center's four field test sites to investigate corrosion in the splash-spray zone, surface waters, and deep ocean water. Vulnerable materials used in wave energy devices and OTEC components will be identified and standard sample coupons and ceramer coatings will

be prepared and tested. The exposed samples will be analyzed in the laboratory to determine corrosion mechanisms and results will be applied to develop second-generation ceramic coatings.

Biocorrosion of sample coupons and actual hydrokinetic devices and OTEC components will also be explored using molecular methods to identify the composition of fouling communities (e.g., 16S or 18S rRNA library construction), classical taxonomic approaches, and Scanning Electron Microscopy. Innovative marine coatings, containing natural compounds extracted from algae and sponges and conductive polymers, will be tested in laboratory to determine if they are effective in providing protection from biocorrosion to ferrous and non-ferrous metals.

In addition to the above research topics, cradle-to-grave carbon footprinting of wave power and OTEC systems will also be conducted to assess the relative merits of these systems with regard to net greenhouse gas emissions.