WAVE ENERGY CONVERTER PERFORMANCE MODELING AND COST OF ELECTRICITY ASSESSMENT

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ABSTRACT

Wave Energy Converter Performance Modeling and Cost of Electricity Assessment

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California is experiencing a rapid increase in interest for the potential of converting ocean waves into clean electricity. Numerous applications have been submitted for the permitting of such renewable energy projects; however the profitability, practicability, and survivability have yet to be proven. Wave energy conversion technology has steadily matured since its naissance in the 1970's, several wave energy power installations currently exist, and numerous plans for commercial power plant are in the works on the shores of multiple continents. This study aims to assess the economic viability of two proposed commercial wave energy power plant projects on the Central California Coast. A theoretical 25 MW capacity wave energy plant located at a site five nautical miles off of Point Arguello, in Santa Barbara County is compared to a site five nautical miles off of Morro Bay, in the County of San Luis Obispo. The Pacific Gas and Electric Company and Green Wave Energy Solutions, LLC have proposed full-scale commercial wave power plants at these sites, and are currently undergoing the federal permitting processes. Historical wave resource statistics from 1980 to 2001 are analyzed with performance specifications for the AquaBuOY, Pelamis P1, and WaveDragon wave energy converters (WECs) to calculate the annual electrical output of each device at each site. Sophisticated computer modeling of the bathymetric influence on the wave resource at each site is presented using the program Simulating Waves Nearshore (SWAN) developed by the Delft University of Technology. The wave energy flux, significant wave height, and peak period are computed at each site for typical summer and winter swell cases, using seafloor depth measurements at a 90 meter rectangular grid resolution. The economic viability of commercial electricity generation is evaluated for each WEC at each site by the calculation of the net present value of an estimated 25-year project life-cycle, the internal rate of return, and the required cost of electricity for a 10-year project simple payback period. The lowest required price of electricity is $0.13/kWh and occurs at the Point Arguello site using the AquaBuOY WEC. The highest annual capacity factor is 18% using the Pelamis WEC. The net present value and internal rate of return calculations suggest that the AquaBuOY WEC is profitable at both sites for electricity prices above $0.14/kWh. Shallow water wave propagation SWAN modeling demonstrated favorable wave energy flux states for WEC operation and power generation at both sites, with typical winter energy fluxes of 30-37 kW/m.

Keywords: Wave energy conversion, site assessment, economic analysis, wave modeling.

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I. INTRODUCTION

Worldwide, a wave of transition has begun in the way electrical power is being generated. For a myriad of geopolitical, environmental, economic, and practical reasons, the benefits of substituting former fossil fuel dependent power generation techniques with new renewable energy methods has recently been realized. Policy makers, industry leaders, and many researchers are actively pursuing measures to capitalize on this paradigm shift and produce efficient, cost effective and renewable energy technologies. Although much attention has been brought to the recent growth of solar, wind, and bio-fuel industries, the technology for generating electricity from ocean waves has been quietly maturing and is on the cusp of implementation in coastal areas worldwide.

Through various thermal processes and energy transformations, much of the solar insolation incident upon the Earth's surface is ultimately concentrated into the oceans through the creation and propagation of ocean waves. Global temperature gradients drive atmospheric winds, which when interacting with the surface of open ocean, creates waves. The duration the wind blows, the distance it covers (fetch), and the speed it blows determines the wave size created. Wind generated waves then travel in groups called wave trains to distant shores at various energy states dependent upon incident seafloor bathymetry and the presence of ocean currents. Ocean waves provide an untapped energy resource with the potential to provide a power-dense, predictable, environmentally-friendly, and widely available source of renewable energy. The global estimate of attainable wave power production is approximately 2 terawatts (TW), a significant portion of the world's current installed electric capacity of 3.5 TW (1). Since 37% of world's population lives within 60 miles of a coastline, it is no surprise that recent interest in wave energy conversion (WEC) technology has spiked, tempting many to capture this immense resource (4).

California exemplifies this match of resource and demand, featuring a high energy wave climate and soaring energy demands. In 2006, California required a power capacity of roughly 32 gigawatts (GW) to meet its energy needs (2). California's energy usage is currently increasing at rate of 1.25% annually, while peak demand is increasing at 1.35 percent per year (3). Additionally, the California Global Warming Solutions Act of 2006 requires that California reduce greenhouse gas emissions by 25% by 2020, with caps on significant sources of emissions beginning in 2012 (4). Recent in-depth analysis and modeling of the entire California wave energy resource found an average wave energy density of 25 kW per meter coastline, a quantity considered sufficient for competitive commercial electricity production using emerging WEC technology (5). The California Energy Commission estimates that California's 1200 miles of usable coastline holds a theoretical potential of 38 GW, with an estimated technical potential of 7 to 8 GW, or roughly one quarter of California's 2006 energy demands (2). Nationally, recent estimates assess the rest of the U.S.'s wave resource as significant as well, as much as 6.5% of current electricity consumption, a capacity equivalent to all current U.S. conventional hydropower installations (6).

This study aims to evaluate two coastal sites in California for their economic viability of the implementation of wave energy conversion for electricity production. The cost of electricity (COE) produced at each site will be calculated for the operation of three WEC technologies, providing a comparison of the two locations and their optimized WEC electrical power production. This evaluation is meant to provide up to date estimates of economic metrics that indicate the feasibility of such an endeavor, and the findings are presented with the expectation that such metrics must be judged against current market conditions and regulatory factors to determine their valuation. Background information including the detailed objectives of the study, an introduction to the topic of ocean wave generation, and a brief overview of WEC device development is also included to provide some context for this assessment. WEC designs and characteristics are further discussed in Section III, and provide technical information about the mechanics of the three WEC devices included in this study. Section IV, *WAVE RESOURCE,* provides background information and methodology used to calculate the available wave power at both of the sites. Section V, *POWER PRODUCED AND ECONOMICS*, provides equations and methodology used to calculate the economic metrics computed in this study, as well as the methods used to calculate the expected power output of each WEC. In Section VI, *REGULATORY HURDLES*, a general description of the wave energy regulatory process is included for reference, a topic indirectly related to the economic analysis of this study, but extraordinarily pertinent to the overall implementation of wave energy conversion. Sections VII through IX include the results, discussion, and conclusion of the report findings and supplementary data and supporting figures are contained in Appendixes A through E.

II. BACKGROUND

The main focus of this study concerns the WEC performance and economic outcome of their deployment, the details of which are outlined in the following Study Objectives section. To better understand the significance of the stated objectives, the subsequent Wave Generation and WEC Development History sections have been included to provide some background information.

Study Objectives

Two Central California locations have been identified for evaluation of their economic viability for the commercial generation of electricity by ocean wave energy conversion. The areas identified in this study are in the general vicinity of actual proposed commercial projects, but the projects analyzed are hypothetical and do not reflect the exact parameters of proposals by the Pacific Gas and Electric Company or Green Wave Energy Solutions. This study aims to evaluate each site’s economic viability for wave energy conversion, independently of any actual proposed projects. Two sites were chosen to include an element of comparability, and although each site has many unique attributes, both locations exhibit very similar parameters. The site areas were chiefly chosen due to their significant probability of future commercial WEC development, demonstrated by several factors: the presence of pending permits with Federal permitting agencies, recent findings of the California Energy Commission’s report *Generating Electricity from Ocean Waves in California*, and independent analysis of historical wave resource statistics (1)(5). The two sites selected for analysis are 5 nautical miles off the coast of Morro Bay, CA (Site A) and 5 nautical miles off the coast of Point Arguello, CA (Site B).

On May 1, 2009, Green Wave Energy Solutions, LLC received a preliminary permit from the Federal Energy Regulatory Commission (FERC) to study the feasibility of commercial wave energy conversion in the general vicinity of Site A. The eventual full scale project advertised called for 100 megawatt (MW) of electrical to produce an expected 250,000 megawatt-hours (MWh) per year. The FERC preliminary permit is valid for three years and provides the opportunity for priority in the commercial licensing process required to build a commercial project. On December 11, 2010, Pacific Gas and Electric Company submitted an application to FERC for a preliminary permit for the generation of electricity from ocean waves in the general vicinity of Site B. Initial plans call for an eventual 100 MW of electricity to be produced and sold directly to Vandenberg Air Force Base per a memorandum of understanding signed between the two parties. Proposed project information and maps of permitted areas and projects are included in Appendix A. Figures 1-3 and Table 1 illustrate the site locations and list coordinates and site specifications analyzed in this study.

Site	Project	Project center latitude	Project center longitude	Average water depth (m)
Morro Bay	Site A	35.3620	-120.9880	97
Point Arguello	Site B	34.6380	-120.7300	75

Table 1. Hypothetical wave energy power plant center point coordinates and depths.

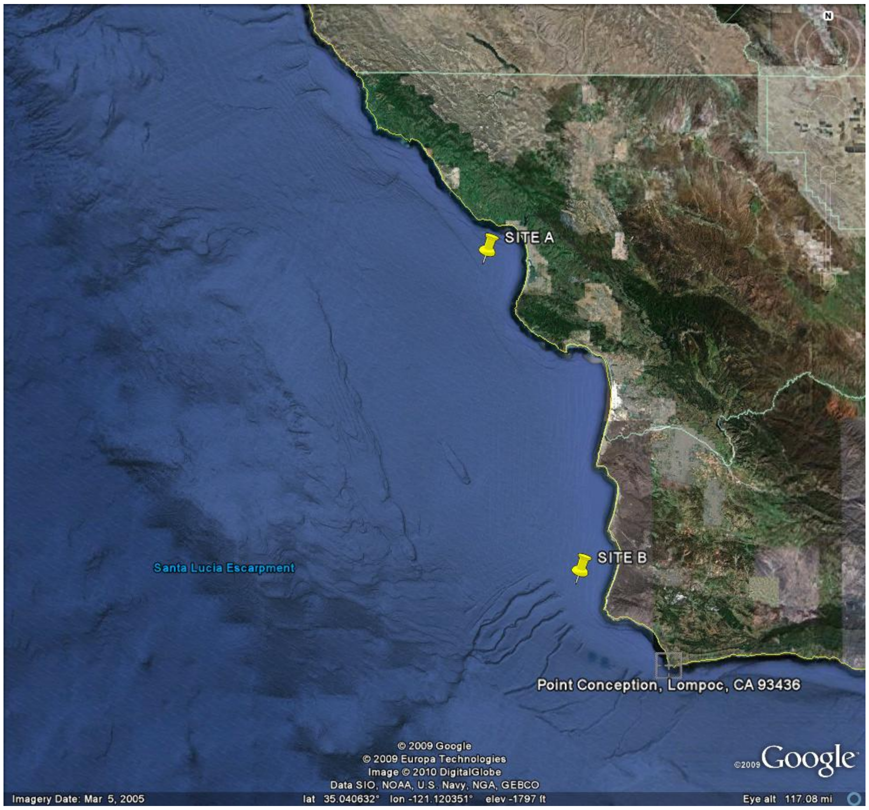

Figure 1. Site A and B locations on Google Earth.

The study objective is to make accurate estimates of economic indicators of the viability of each site for electrical generation at a commercial scale. A plant capacity of 25 MW of electricity is assumed, which industry experience suggests would produce a predicted average of 65 GWh per year (7). General specifications for each hypothetical plant have been made similar to preserve comparability, and attributes such as available grid connection points, size of nearby population centers, and distance to port can be assumed to be equivalent for both sites. A distance of 5 nautical miles from shore was chosen to reflect the location of the proposed commercial project proposals, which also reflects the regulatory boundary between State and Federal waters, and allows for adequate depth to minimize wave energy flux losses from seafloor friction. Emphasis has been placed on comparison of WEC device performance at the identified locations, and the wave power plant capital and operational costs necessary for production of the targeted power plant capacity. Included in capital costs are all plant infrastructure needs such as the sub-sea cable connection and WEC mooring installations. Comprehensive lists of cost parameters analyzed are included in the POWER PRODUCED AND ECONOMICS section.

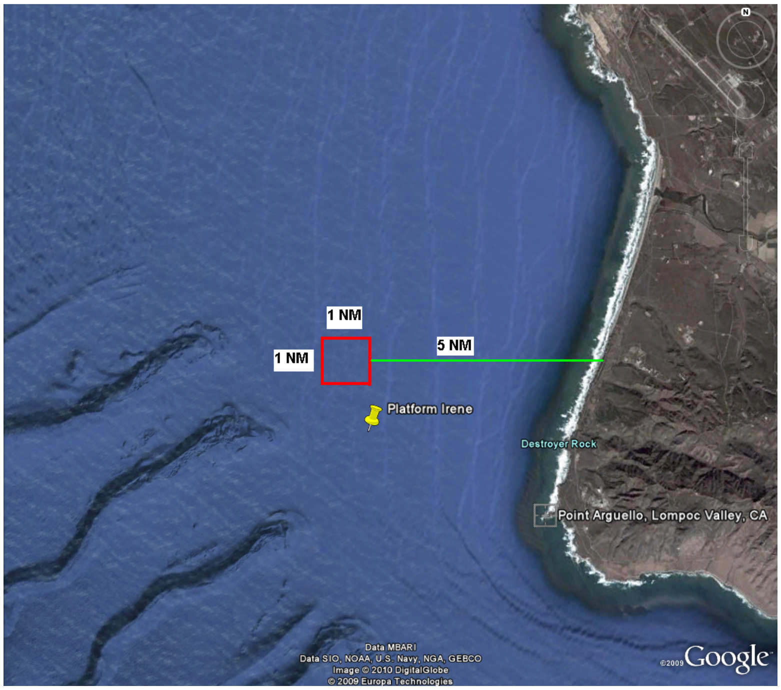

Figure 2. Detail of Site A location

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Figure 3. Detail of Site B location.

Wave Generation

To better understand the wave resource potential and wave energy extraction methods described in this study, the following is a brief review of ocean wave mechanics. A variety of mechanisms can create waves in the ocean, such as opposing current and the movement of boats, but by far the most common means is the effect of friction on the water's surface from the interaction with wind. Wind events that occur over bodies of water create an irregular wave field comprised of an assortment of wave orientations, frequencies, and speeds. Waves created in a storm typically look chaotic, highly unorganized, and are characterized by short-crested, short-period waves that are often steep and varied in height. Three determining factors dictate the wave characteristics in a wind induced wave creation event. The fetch, described as the distance over which the wind blows without a change in direction, the duration of the wind event, and the wind velocity can each potentially limit the wave characteristics created. If all three of these factors are presently sufficient, there is a maximum wave height limitation due to the dissipation of energy via wave breaking or "whitecapping" of the waves. A storm event of this nature is described as containing "fully developed seas."

Figure 4. Fully developed sea state.

The irregular nature of a wave field in a fully developed sea state or of any other sea state containing waves of variable frequency and direction can be accurately represented by the summation of a large number of regular sinusoidal wave components using the method of spectral wave analysis. Spectral wave analysis utilizes this model to accurately represent the resultant wave parameters as a product of the complete wave frequency, amplitude and directional spectrums. Figure 5 illustrates the separation of an irregular sea state into a variety of spectral components.

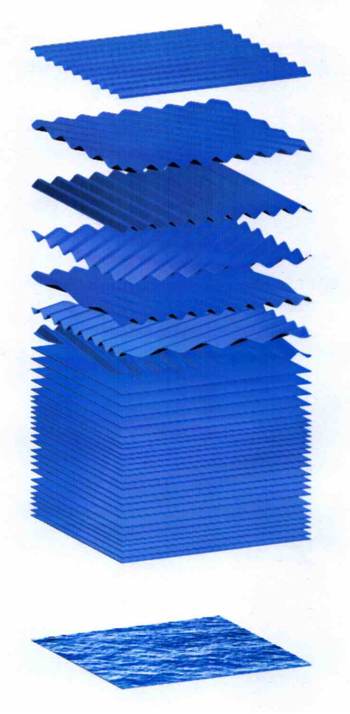


Figure 5. Irregular sea state separated into spectral wave components (2).

As long as nonlinear effects are insignificant, meaning that the spectrum is consistent over a few wavelengths in size, and if bottom and current effects remain constant over this area, the individual wave phases are assumed to be uncorrelated to each other. Spectral analysis is useful in determining which frequencies and directions are significant in a complex sea state, which can then be used to determine which frequencies have the greatest wave energy content.

As waves propagate away from storm events, they begin to organize themselves into ocean swells, long crested waves arranged with respect to frequency and speed. Groups of swells produced from a common storm event, called wave trains, travel great distances with minimal change in wave characteristics when crossing deep bodies of water. Open ocean swells closely resemble the simple sinusoidal or monochromatic waves that are individually analyzed in spectral analysis. Figure 6 describes terms related to sine wave elements as they will be referred to in this study.

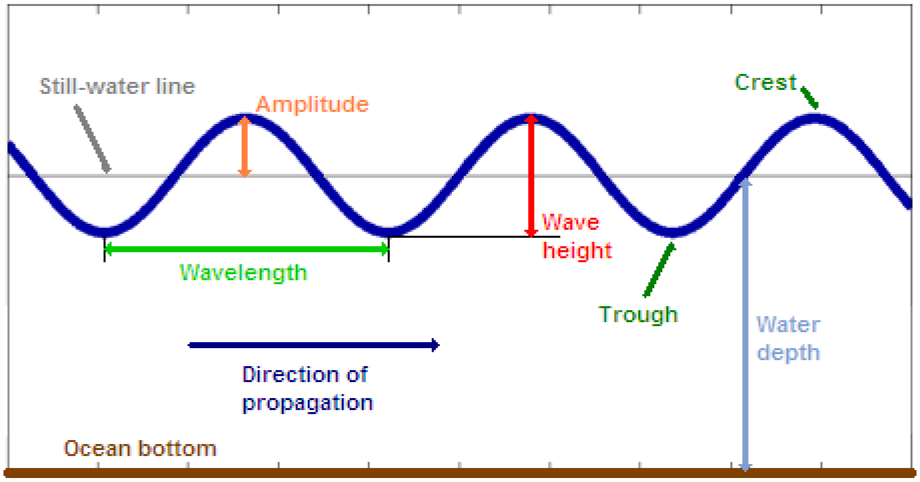


Figure 6. Sine wave element terminology (8).

It is important to realize that contrary to casual observation, open ocean waves in deep water do not transport any volume of water in their direction of travel. At the individual water particle level, or for example, at a floating point on the surface of the water, movement is strictly in a circular path. The wave itself is a disturbance of the surface of the water created by the flow of energy, not the flow of water.

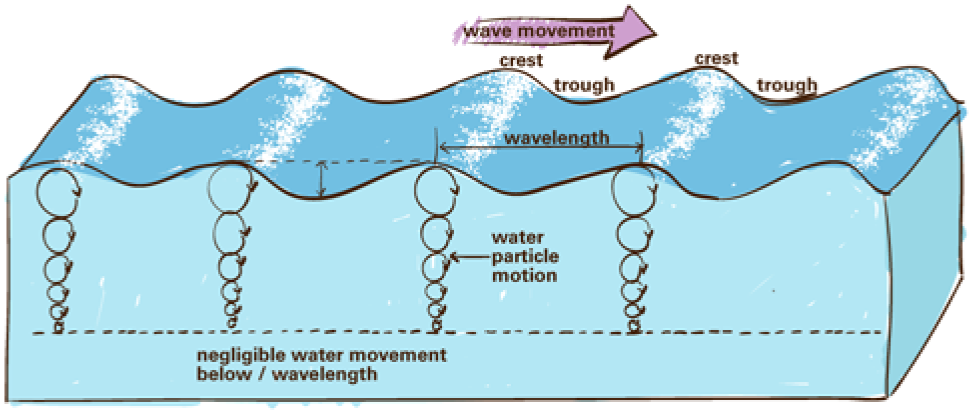


Figure 7. Water particle motion in ocean waves (8).

As water depth decreases near shorelines, the orbital oscillations of the water column begin to be influenced by the ocean floor. The circular paths of water particles in the water column begin to “feel” the seafloor and become elliptical in shape. The depth of water at which this interaction begins is dependent upon the magnitude and frequency of the wave, and is often characterized as water depth one half of the wavelength. For the purpose of ocean waves relevant to WEC, the 100m depth contour can be defined as this boundary (9). In the presence of the seafloor, bottom friction causes water particle oscillations decrease in the vertical dimension, slowing the wave and beginning the wave breaking process. This process is known as “shoaling,” and results in the steepening of the wave, increasing the wave height and decreasing the wavelength. The depth at which the seafloor generates this effect defines the boundary inside of which is referred to as “shallow water.” Additionally, seafloor bathymetry also induces wave refraction, causing wave crests to bend and become parallel to the shoreline. Once the wave height reaches a critical point for a given wavelength, it becomes unstable and breaks, dissipating its energy. The wave period remains constant through the shoaling process, and broken waves can reform and break multiple times at incrementally lower energy states until their ultimate termination at shore.

WEC Development History

Wave energy conversion in California can be traced back to 1898 when inventors William and John E. Armstrong installed a wave actuated pump on the bluffs of Santa Cruz to force water into an elevated tank used for filling water wagons that watered roads to keep down the dust (10). In recent decades, WEC technology gained a brief spike in interest during the oil crisis of the 1970's, but by far has seen the most exciting developments in the last ten years. Over 1000 patents have been filed in the last 50 years for WEC devices, and over 100 companies have attempted commercial use of their designs worldwide (1).

The first noteworthy WEC was invented in the 1970's by Stephen Salter at the University of Edinburgh and was known "Salter's Duck." Salter gained considerable attention at the time by boasting 90% energy absorption from waves in tank testing (11). Design limitations and problems associated with increasing the scale of the device prevented Salter's Duck from large scale testing or sea trials, and none of the emerging commercial WEC designs today closely resemble the Salter Duck.

The first device installed to produce electricity from ocean waves was the Pico Power Plant, built in 1999 on the Island of Pico, in the Azores, Portugal. The Pico device was an onshore system that utilized variable pneumatic pressures in an enclosed chamber to run a turbine, a WEC configuration known as an oscillating water column. The project has been in intermittent operation ever since, overcoming a series of technical difficulties during its service life, and has just recently achieved some great performance improvements. In tests and trial periods from 2005 to 2006, a total of 1MWh of electricity was produced. However, after turbine reconfiguration, nearly 1MWh was produced in one 48hr period alone during a May 2009 test. Currently, the plant is still operational and is managed by the Portuguese consortium called the Wave Energy Centre (WavEC).

Figure 8. Oscillating water column wave energy converter at the European Wave Energy Center, on the island of Pico, Portugal.

The first commercial WEC plant connected to a utility grid was Pelamis WEC designed and built by the Scottish company Ocean Power Delivery (OPD) (OPD has since changed its name to Pelamis Wave Power). The device was first commercially launched at full scale at the Aquçadoura wave farm in Northern Portugal. Three 750 kW P1-A Pelamis Wave energy converters were installed in October of 2006, and are now owned and operated by the Portuguese utility Energais de Portugal. A recent letter of intent from Energais de Portugal announced plans for the purchase of an additional 20MW of Pelamis WECs, and according to Pelamis Wave Power's website, the development process for this extension is currently underway.

A handful of other WEC manufactures have since deployed both scale and full size prototypes in sea trials and have successfully generated electricity. More details about these devices will be included later in the WEC Design Characterization section of this report. A great asset to recent WEC development and testing has been the recent availability of quality WEC testing facilities. The most prominent of which is the European Marine Energy Centre (EMEC), located in the Orkney Islands of Scotland. EMEC provides grid connected sea trial test beds as well as comprehensive weather and performance modeling. Prominent WEC manufacturers such as Pelamis Wave Power have utilized EMEC facilities for their initial full scale prototype deployments and testing.

Domestically, wave energy research has been primarily been carried out at Oregon State University (OSU), the University of Hawaii (UH), University of Washington (UW), and the University of Massachusetts (UM). The recent Energy Independence and Security Act of 2007 (H. R. 6) includes provisions for Federal funding to establish three new National Marine Renewable Energy Test Centers. The three US test centers that have received resources as a result the ruling have been OSU-UW, UH, and UW. The US Department of Energy (DOE) awarded $6.5 million over five years beginning in 2008 to fund the Northwest National Marine Renewable Energy Center (NNMREC), a partnership between OSU, UW, and the National Renewable Energy Laboratory. NMMREC's goals are to support wave and tidal energy development in the US and function as a test center for domestic and international WEC developers. NMMREC also has goals to inform regulatory policy decision makers and close gaps in understanding of WEC deployment and operation. The DOE also awarded $5 million grant in 2008 to be paid over five years to fund the Hawaii Natural Energy Institute (HNEI) at the University of Hawaii School of Ocean and Earth Science and Technology. HNEI research will be centered on research and development of wave energy and ocean thermal energy conversion technologies.

In June of 2009, the DOE awarded $950,000 to the New England Marine Renewable Energy Center (NEMREC), located at the University of Massachusetts Dartmouth Advanced Technology and Manufacturing Center. NEMREC is an organization of academics, industry, and government agencies with the goal of supporting wave tidal, and offshore wind energy development on the Eastern US Coast. NEMREC has plans for construction of a full scale WEC test and demonstration site off the coast of Martha's Vineyard and Nantucket.

As marine renewable energy industry momentum has built in the recent years, many industrial organizations and interest groups have been formed to foster governmental support, business segment cohesion, and community stakeholder involvement. The Ocean Renewable Energy Coalition (OREC), founded in 2005, is national trade organization that promotes industry interests from a wide range of ocean renewable energy sectors including wave, tide, offshore wind, ocean current, ocean thermal, and marine biomass industries. OREC advocates for its member's interests with political lobbying campaigns and the hosting of industry conferences. An example of one of the many interest groups formed around wave energy development is the Oregon Wave Energy Trust, a non-profit public-private partnership formed to provide a medium for collaboration between local stakeholders, regional planners, and the marine renewable energy industry.

III. WAVE ENERGY CONVERTERS

WEC Design Characterization

Wave energy converters can be categorized into three categories based on how they capture the mechanical energy of ocean waves. The industry-accepted classes of WEC designs are point absorbers, attenuators, and terminators. Each design class uses a different method of converting wave energy to a useful form of mechanical energy. The wave energy industry has yet to converge on a single WEC design class that is superior, and WEC manufactures are in the process of actively testing all three categories to make that determination.

Point absorbers are characterized by device designs with very small surface areas in comparison to the wavelength of ocean waves. Most designs consist of a moving buoyant section that reacts with a stationary component to create a pressurized displacement volume that can be readily utilized. Most point absorber devices take advantage of the vertical component of passing ocean waves, acting as a simple pump, and translate the kinetic energy of the vertical movement by pressurizing seawater or hydraulic fluid. Energy is then extracted from the pressurized fluid using a variety of power take off (PTO) mechanisms that will be described in better detail in a later section. The moving and stationary components of a point absorber design can be located near the seafloor or at the surface, and prototypes from different WEC manufacturers are designed for a variety of depths. Some notable point absorber WECs under development are the AquaBuOY (Finavera Renewables), PowerBuoy (Ocean Power Technologies), OE Buoy (Ocean Energy Ltd.), CETO (Renewable Energy Holdings), Archimedes Waveswing (AWS Ocean Energy Ltd.) and the Wavebob™ (Wavebob Ltd.).

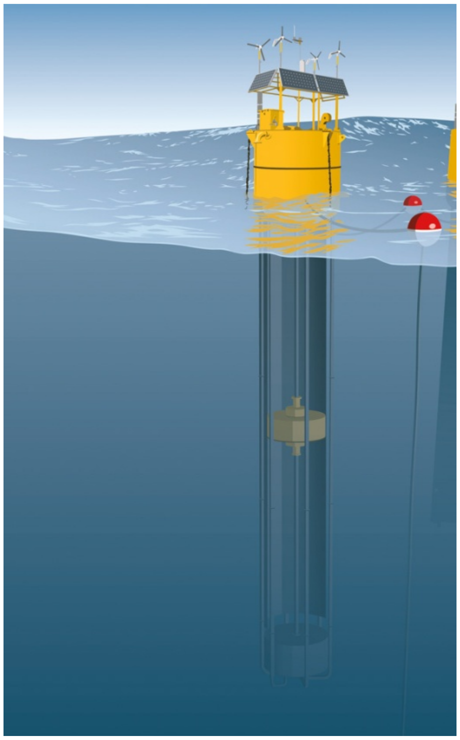


Figure 9. Point absorber WEC, Finavera Renewables AquaBuOY.

Attenuator devices are relatively long in length (up to 150m) as compared to ocean wavelengths, and are typically positioned in parallel to the general direction of wave propagation. Attenuators consist of multiple buoyant segments that articulate as wave crests and troughs pass. Mechanical energy is extracted from the relative motion of each segment, usually though the compression of a fluid in hydraulic pistons. Attenuators can be designed to float freely and operate at the water's surface or can be arranged to articulate in reaction to a fixed structure attached to the ocean floor. Notable attenuator WECs under development are the Pelamis P1 (Pelamis Wave Power), Oyster^{Ra} (Aquamarine Power), bioWave™ (Bio Power Systems), and Ocean Treader (Green Ocean Energy Ltd.).

Figure 10. Attenuator WEC, Pelamis P1.

Terminator wave energy convertors are designed to absorb the entire, or a large portion of, energy content of incident waves. Terminators are typically oriented perpendicular to wave crests and can be designed for open ocean or shore mounted deployment. In terminator WECs, wave energy is converted to useful energy in one of two ways: overtopping, or through the use of an oscillating water column (OWC). Overtopping terminators are situated slightly above the water's surface and have an elevated basin. As wave crests approach, water travels up inclined troughs into the raised basin, and then returns through the center of the WEC, on its way passing through a low-head turbine that extracts the potential energy of the elevated water. The low head water turbines used in overtopping devices have been adapted directly from available technology in the hydropower industry and produce relatively high efficiencies (1). Variable speed power conversion systems on such overtopping systems allow for the convenient adjustment of flow rate and variable power output, increasing the quality of the electric power produced. The most notable overtopping terminator WEC is the WaveDragon (WaveDragon ApS.).

Figure 11. Overtopping terminator WEC, WaveDragon.

OWC terminators are also located at the surface of the water and consist of an air filled chamber with an opening submerged under water. As waves pass under the submerged opening, the water height inside the chamber rises and falls with the associated crests and troughs. The fluctuating volume of air inside the chamber creates alternating positive and negative pressure gradients with the external atmosphere powering a pneumatic turbine to produce readily accessible mechanical energy. A common turbine used for OWC WECs is the bidirectional Wells turbine, which converts the bi-directional air flow from the OWC chamber into unidirectional output using symmetrical aerofoil blades that spin in a constant direction irrespective of air flow. Notable OWC terminators under development are the Oceanlinx (Oceanlinx, formerly Energetech), and the shore-mounted Limpet (Wave Gen), and the Pico plant at the European Wave Energy Center.

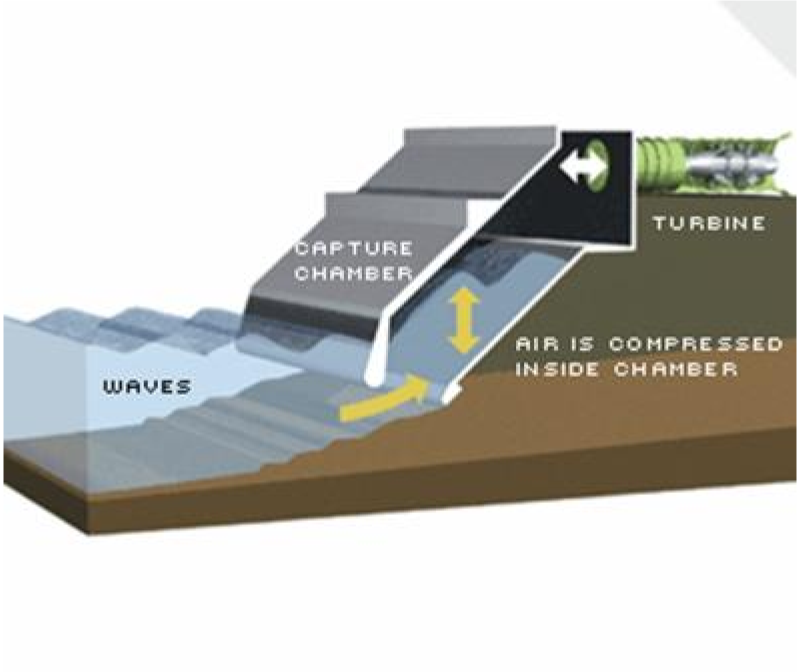


Figure 12. Oscillating water column WEC schematic, Pico, Portugal.

Power Take Off

Regardless of WEC configuration, all WECs require mechanisms to convert extracted wave energy into electricity, or another readily usable energy form. The power take off is an important component in the efficiency train that greatly influences overall device efficiency, device cost, required maintenance schedule, as well as the quality of electrical power. Attenuators and some point absorber designs that feature hydraulic power conversion systems are advantageous for several reasons. The high- pressures of hydraulic systems minimize fluid dynamic losses, allowing for efficiencies of 70-80% in typical systems consisting of volumetric displacement pumps and standard generators (14). Volumetric displacement pumps are used to convert the slow movement of WEC components into hydraulic pressure that can be used to drive hydraulic motors, and ultimately an electric generator. Hydraulic systems also have the advantage of allowing for hydraulic accumulators that can tailor flow outputs to meet power generation component requirements, increasing the quality of the power produced. Most marine hydraulic component technology is also readily available due to the offshore oil and gas industry (1). Several WEC designs utilize hydraulic PTO systems with working fluids other than conventional hydraulic oils. WECs such as the CETO and AquaBuOY compress seawater using volumetric pumps and efficiently extract rotational mechanical energy by applying water flow to Pelton wheel style turbines.

Despite the many advantages of hydraulic PTO systems, they are by no means the industry standard. Pneumatic PTO systems are preferred by many in the WEC community, and more than half of existing WECs are air driven (12). Although there are various other configurations, the most widely used air driven system is the OWC. The Wells turbine utilizes the bi-directional capabilities of self –rectifying turbines to attain maximum power conversion efficiencies of around 60%, with average efficiencies between 25-40% (1)(12). Performance enhancing design measures such as variable pitch vanes can further increase Wells turbine efficiency up to 70-80% (12). Wells turbines also have the added advantage of relatively inexpensive manufacturing costs due to their symmetrical blade geometry.

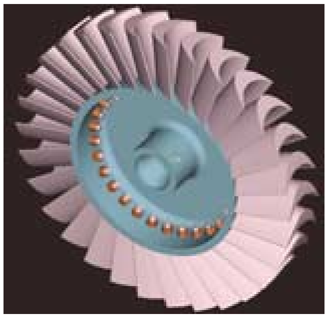


Figure 13. Bi-directional Wells turbine (14).

Emerging Commercial WECs

Although there are literally hundreds of WEC designs that hold patents in a wide variety of countries, for the purpose of this study three WEC devices were chosen for analysis for several key reasons. Each WEC analyzed has successfully demonstrated or is near to full-scale prototype deployment in real ocean conditions, has reasonable funding for continued development, has provided or made publicly available expected performance specifications, and has publicly disclosed device cost estimates. These parameters were chosen out of necessity for the information required to fulfill this study and narrowed the potential field of WECs to be considered to the AquaBuOY, Pelamis, and WaveDragon. This selection also sufficiently represents WECs from each of the three design categories mentioned earlier. Although there are many other promising WEC devices in existence, none others met the necessary criteria and were therefore excluded in this study's site assessments. In an effort to prevent the marginalization of other promising WEC designs, several other WECs that fell just short the study parameters are discussed at the end of this section. The three WECs selected for inclusion in this study have met similar or more stringent requirements in other published works, and are believed to be closest to commercial scale deployment.

AquaBuOY

Finavera Renewables acquired the AquaBuOY design form the AquaEnergy Group in 2006. The point absorber WEC is 6m in diameter, a draft of 30m, and rated to 250 kW depending on the sea state. It floats freely on a slack moored system, and is designed for deployment in water depths greater than 50m. The AquaBuOY consists of a submerged tube containing a mass of water, within which is a piston assembly. As waves pass, the piston/tube assembly reacts against the heaving buoyant buoy at the surface, acting as a pump and pressurizing the piston. The pressurized seawater is then fed to a hydraulic accumulator which smoothes the power output between wave cycles. The pressure head is then discharged into an impulse turbine coupled to an internal electric generator. Grid synchronization for commercial arrays of AquaBuOYs would be accomplished prior to power transmission to shore at submerged substations, using step-up transformers and variable speed AC-DC converters. The AquaBuOY utilizes a steel structure and is designed to be transported and serviced when floated into a horizontal position.

A significant design limitation of the current AquaBuOY system is the accumulator in the power take off system. The method tuning the device for local wave conditions consists of slowly adjusting the pressure level in the hydraulic accumulator. Overall power absorption is then limited by only allowing for the device to tune to the dominant wave periods, instead of dynamically adjusting to each wave that passes through, as some other WECs are capable of.

In September of 2007, Finavera Renewables deployed an AquaBuOY 2.0 prototype at a pilot project site in Makah Bay, Washington. The prototype reportedly operated successfully for a short period of time but unfortunately sank shortly after its deployment in October of that year. Since, Finavera Renewables has turned its efforts to an improved design of the AquaBuOY 3.0, which is currently under development. In December of 2007, Finavera Renewables signed a 2 MW commercial wave power purchasing agreement with the utility Pacific Gas and Electric Company at a site offshore of Humboldt, California. The Pacific Gas and Electric Company has since secured a preliminary permit from the Federal Energy Regulatory Committee (FERC) and plans to generate power at the site in 2012.

Pelamis

Pelamis Wave Power (formerly Ocean Power Delivery) was founded in 1998 by Dr. Richard Yem, Dr. Dave Pizar, and Dr. Chris Retzier, and is responsible for the development of the Pelamis P1 and P2. Pelamis WECs are of the attenuator design characterization and consists of 4 tubular sections hinged together that float freely at the water surface. Constructed of steel, the total device length is 150m and the diameter of each tube is 4.63m. Each of three hinged connections between tubular sections contains 3 digitally controlled hydraulic rams which convert the relative articulation of each buoyant section into hydraulic pressure. Internal accumulators and twin 125 kW generator sets convert hydraulic power into electricity. Biodegradable hydraulic fluids are used in all rams to minimize environmental damage in case of a spill. Overall device power output is rated at 750 kW depending on wave conditions. Each device is designed for a freely rotating 3-point slack mooring and is intended for deployment in water depths greater than 50m. Commercial wave power plant arrays would be configured with seafloor mounted junction boxes interconnecting individual Pelamis WECs with flexible riser cables that linked each WEC to the seafloor. Internally, each Pelamis features a frequency inverter and step-up transformer for grid synchronization.

Three Pelamis P1 WECs were deployed in Northern Portugal in 2006 and are currently still operational. Pelamis Wave Power plans for the first sea trials to the P2 WEC to commence sometime in 2010 for grid connected testing at EMEC in Scotland. An additional three Pelamis WECs are slated to be permanently installed at EMEC in a project lead by the Scottish Power Renewables utility in a project that will be called the Orcadian Wave Farm.

WaveDragon

The WaveDragon is an overtopping terminator device invented by Erik Frlis-Madsen and is constructed using a combination of steel and reinforced concrete. Including its extended reflector arms, the device measures 300m in width and 170m in length, including a central floating platform that is 140m wide and 67m long. It accumulates incident wave action within its reflector arms and directs water flow up into a raised basin. The potential energy of the captures water is extracted using a number of Kaplan Turbines. The Kaplan Turbines have been adapted for variable speed operation and have design features such as direct drive permanent magnet generators to reduce potential gearbox problems. The raised reservoir has a capacity of 8,000 cubic meters of seawater and the full scale device is rated at 4 MW, and requires placement in 25m of water depth or greater. Onboard step up transformers and frequency converters are used for grid synchronization and the device can adjust to variable wave climates by raising or lowering the waterline with adjustable ballast systems. The Wave Dragon is one of the largest WECs in capacity and size that is under development, potentially providing an economy of scale that other devices lack.

The Wave Dragon is the only WEC included in this study that has not yet demonstrated their design at full scale. A grid connected 1:4.5 scale prototype was deployed in 2003 of the Coast of Denmark and successfully completed over 2,000 hours of sea trials. Wave Dragon is currently raising capital for a 7 MW WEC deployment, with construction slated to begin in 2010.

WEC	Manufacturer	Category	Power rating	Dimensions	Required deployment depth
AquaBuOY	Finarvera Renewables	Point absorber	250 kW	Diameter: 6m Draft: 30m	>50 meters
Pelamis P1	Pelamis Wave Power	Attenuator	750 kW	Diameter: 4.63m Length: 150m	>50 meters
Wave Dragon	Wave Dragon	Overtopping terminator	4 MW	Width: 140m Length: 67m	>25 meters

Table 2. Specifications of WEC designs included in study.

Other Emerging WECs

A number of additional WECs are at or beyond the development stages of the WECs included in the analysis of this study but were excluded for several reasons. Chiefly, performance specifications were limited to that of devices whose performance specifications had already been published. Due to the emergent nature of the wave power industry, many manufacturers declined to provide information when contacted for participation in this study, citing concerns of proprietary information and the potential compromising of competitive advantage.

Some notable emerging WECs that were not included for this reason or that failed to meet other selection criteria mentioned earlier are (manufacturer listed in parenthesis): CETO (Renewable Energy Holdings), Wavebob (Wavebob Ltd.), PowerBuoy (Ocean Power Technologies), Oyster^{Ra} (Aquamarine Power), Archimedes Waveswing (AWS Ocean Energy), bioWave TM (Bio Power), Wave Treader (Green Ocean), OE Buoy (Ocean Energy Ltd.), and Oceanlinx (Oceanlinx).

IV. WAVE RESOURCE

Evaluation of the Wave Resource

An important parameter in determining WEC placement and performance is the wave resource available in the area that the WEC will operate. The wave resource at any given location is the resultant of a multitude of factors including seafloor bathymetry, seasonal sea state variations, and the annual dominant synoptic weather conditions (*i.e. el Niño events*). Ocean waves are created at sea with widely variable frequencies as a result of wind and storm events. The lower-frequency waves, known as swells, propagate great distances in open ocean with very little or no energy loss. Waves traveling in the open ocean, independent of seafloor conditions, are referred to as existing in deep water. As swells leave the open ocean environment, friction from interaction with the seafloor begins the dissipation process that ultimately results in a breaking wave. This condition typically becomes evident inside of the 100-meter depth contour, commonly referred to as the shallow water region. In shallow water, bottom effects and the associated refraction generates spatially inhomogeneous wave parameters that are highly bathymetrically specific. Because the bottom effects play such a significant role in the wave parameters in shallow water, and the fact that most WEC placements will likely be in less than 100 meters of water to minimize transmission and anchoring costs, any complete wave resource analysis must consider both open ocean and near-shore wave and bathymetry conditions. To accomplish this goal, wave parameters must be accurately described at all depths from deep water into shore, utilizing a variety of ocean modeling and measuring methods.

Calculating Wave Power

The wave power available at a given location is a function of significant wave height and the dominant wave period, and can be characterized in terms of energy flux, or wave power density. Typically expressed in units of wave power per meter of crest, the wave energy flux is proportional to the wave period and to the wave height squared. Equation 1 can be used to calculate wave energy flux (E) in units of kilowatts per meter of wave crest (15) (16).

$$E = 0.422 H_s^2 T_P$$ **Equation (1**)

Where T_P is the dominant wave period and H_S is the significant wave height. The inverse of T_P is defined by the peak of the average wave spectra, and H_S is derived from the frequency spectra and is approximated by four times the standard deviation of a wave buoy elevation record. This definition for H_S is used instead of the historical time-domain definition of the average height (crest to trough) of the largest one-third of waves in a given time period. This definition is used to maintain consistency with wave buoy and model data outputs that use the spectral definition of H_S.

Deep Water Wave Statistics

As mentioned earlier, both significant wave height and dominant wave period are highly dependent upon seafloor conditions when in shallow water. In order to set boundary conditions for computational models that describe shallow water conditions, deep water wave parameters must be established. Primarily two means are available for obtaining these parameters, observation and modeling. Observational means utilize either direct measurement via gauging stations in deep water located on buoys or offshore structures, or remote sensing methods using satellite altimeters. Two resources referenced in recent California wave resource studies for such buoy measurements are the National Data Buoy Center (NDBC) and the Coastal Data Information Program (CDIP). The most widely used global ocean forecasting wave model has been developed by the Marine and Analysis Branch of the National Oceanic and Atmospheric Administration (NOAA) and is called WaveWatch III (NWW3).

The NBDC provides data from 60 buoys and 60 Coastal-Marine Automated Network stations. All buoy stations, a large amount of which are located in 100m of depth or greater, measure sea surface temperature, wave height, and wave period. Several of NBDC buoys are located in deep water in close proximity to both Morro Bay and Point Arguello. See Table 3 for coordinates and depths of NBDC stations relevant to this study.

The CDIP maintains more than 80 wave monitoring stations nationally, and is operated through the Center for Coastal Studies at Scripps Institute of Oceanography, University of California at San Diego. In addition to wave height and period, some CDIP buoys also measure directional properties of the wave field. See Table 3 for coordinates and measuring abilities of CDIP buoys relevant to the locations analyzed in this study.

NWW3 is a sophisticated wind-wave model that can perform continuous forecasts of wave climates on a global scale. It numerically solves the spectral action density balance equation for directional spectra, and takes wind and sea ice inputs from the US National Center for Environmental Prediction (NCEP). NWW3 is run continuously in real time for the Pacific, Atlantic, and Indian Oceans and projections can be obtained readily through the World Wide Web. NWW3 projections have been extensively validated by sea buoy observations and remote satellite detection methods. For the purposes of this study, historical buoy data will be used for wave resource and WEC performance modeling.

Station	**Location**	**Latitude (Degrees North)**	**Longitude (Degrees South)**	**Depth (m)**	**Data Coverage**
CDIP 0076	Diablo Canyon	35.21	120.86	22.9	1983-2002
NBDC 46062	Point San Luis	35.10	121.00	379.0	1197-2001
NBDC 46011	Santa Maria	34.88	128.87	185.9	1980-2001
NBDC 46023	Point Arguello	34.71	120.97	384.1	1982-2001
CDIP 0120	Pt. Arguello Harbor Outer	34.57	120.63	5.8	1978-1979
CDIP 0019	Pt. Arguello Harbor Inner	34.57	120.63	2.5	1978-1980

Table 3. NBDC and CDIP buoy records analyzed.

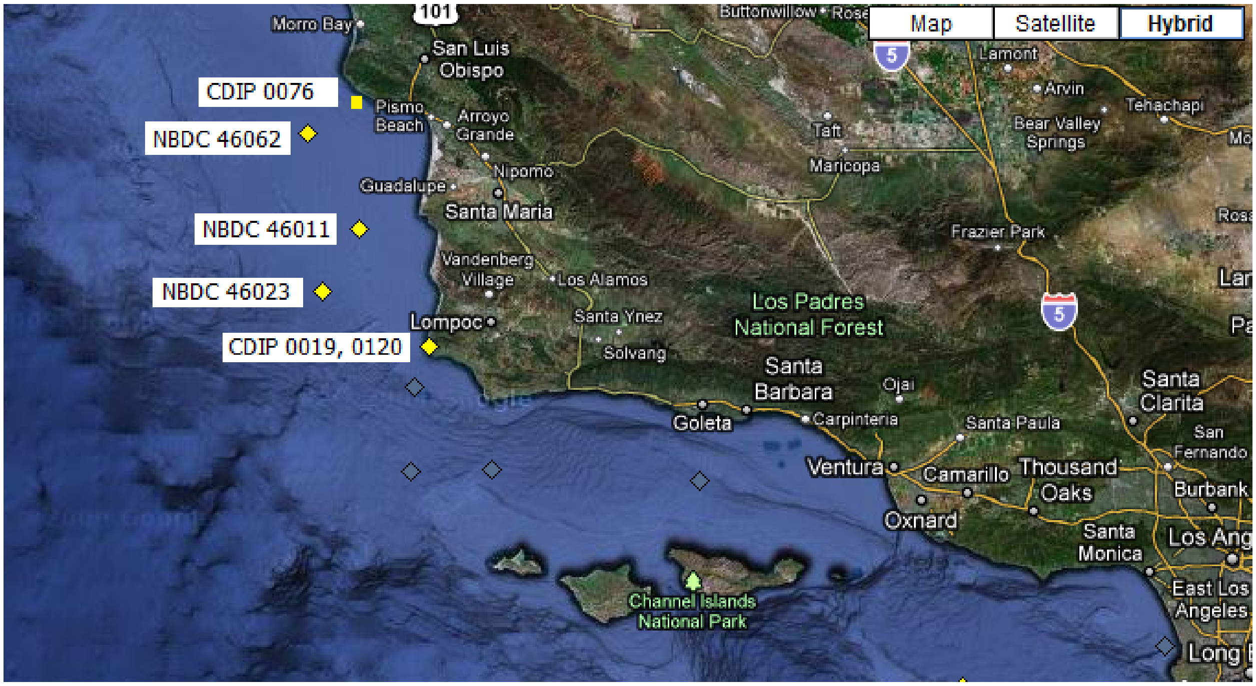


Figure 14. Google Earth image of CDIP and NBDC stations used in study.

Shallow Water Wave Propagation

Once deep water wave statistics have been established for the boundary conditions of a WEC site, great care must be taken to predict the wave characteristics as the waves propagate towards shore. Simulating Waves Nearshore (SWAN) is a wave model that estimates wave characteristics for coastal waters with inputs for seafloor contours, wind field, current flows, and water elevations. Developed by the Delft University of Technology, SWAN is capable of outputs such as refraction, depth-induced breaking, bottom friction, shoaling, wave generation by wind, blocking of waves by current, and nonlinear wave to wave interactions.

SWAN was the model used for the determination of WEC site wave characteristics in this analysis and was run with a variety of deep water wave boundary conditions in order to calculate the expected wave resources available at the Morro Bay and Point Arguello sites.

Bathymetry inputs for SWAN runs executed in this study have been primarily comprised of data provided through the Southern California Ocean Observing System (SCCOOS) and collected by the National Geophysical Data Center (15). The data set obtained contained 2436721 data points at an approximate 90 meter rectangular grid resolution and covered the latitude range of 35.5500 to 34.2500 and longitude range of -121.500 to -120.200. See figure 15 for an illustration of the bathymetrical input field used for SWAN wave propagation runs compiled in this study.

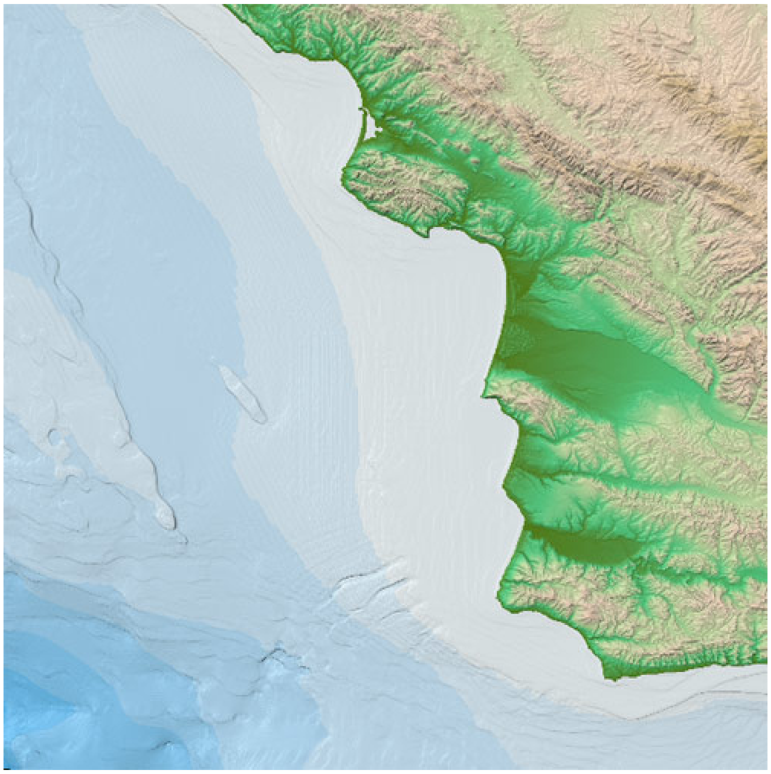


Figure 15. Illustration of SCCOOOS data set input (15).

V. POWER PRODUCED AND ECONOMICS

The economic feasibility of wave power plants at the Point Arguello and Morro Bay sites were investigated by the analysis of two primary metrics, the cost of electricity (COE) for a simple payback period of 10 years, and the 25-year life-cycle cost (LCC) for each WEC design installed in a 25 MW capacity wave power plant. All efforts were made to be all inclusive of capital and operational costs, however due to the present deficiency of WEC commercial deployment industry experience, costs are primarily expressed as approximations and include a margin of error. Current industry costs have been cited when available; however the magnitude of error for such total cost estimations for WEC components is typically +35/-25% (4). The COE is defined as the required cost, expressed in US dollars per kilowatt-hour of electricity produced, to be received by the wave energy plant in order to provide sufficient accumulative revenues to equal the total capital expenditures. In the calculations and analysis presented in the rest of the paper, the term Price of electricity (P_{elec}) shall be used interchangeably with COE, and reflect the wholesale market price for electricity generation. The LCC is the net-present value of all costs minus all revenues over a 25-year period (14). The methodology for reaching COE and LCC metrics of economic feasibility are summarized in Figure 16.

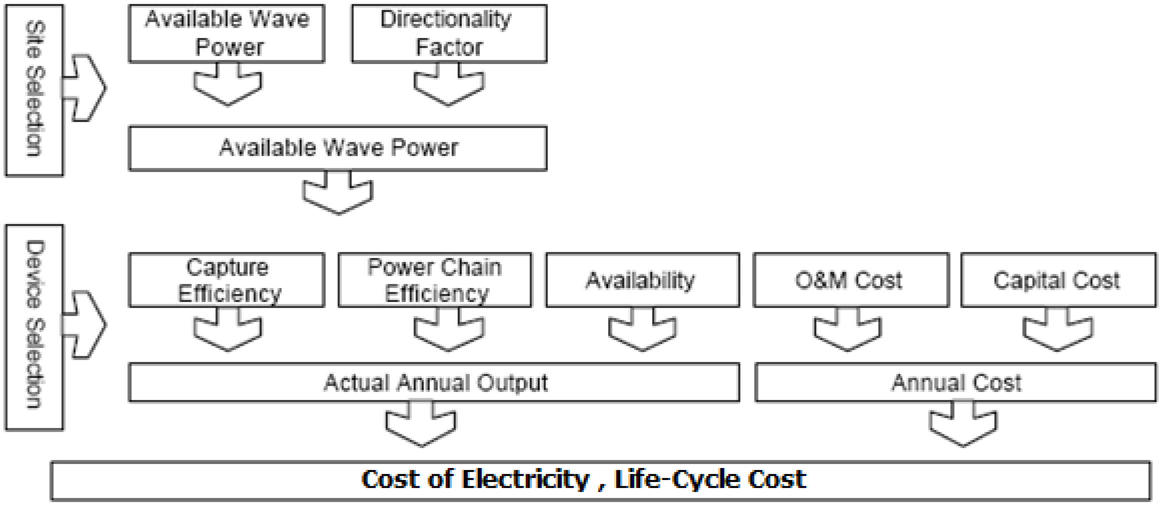
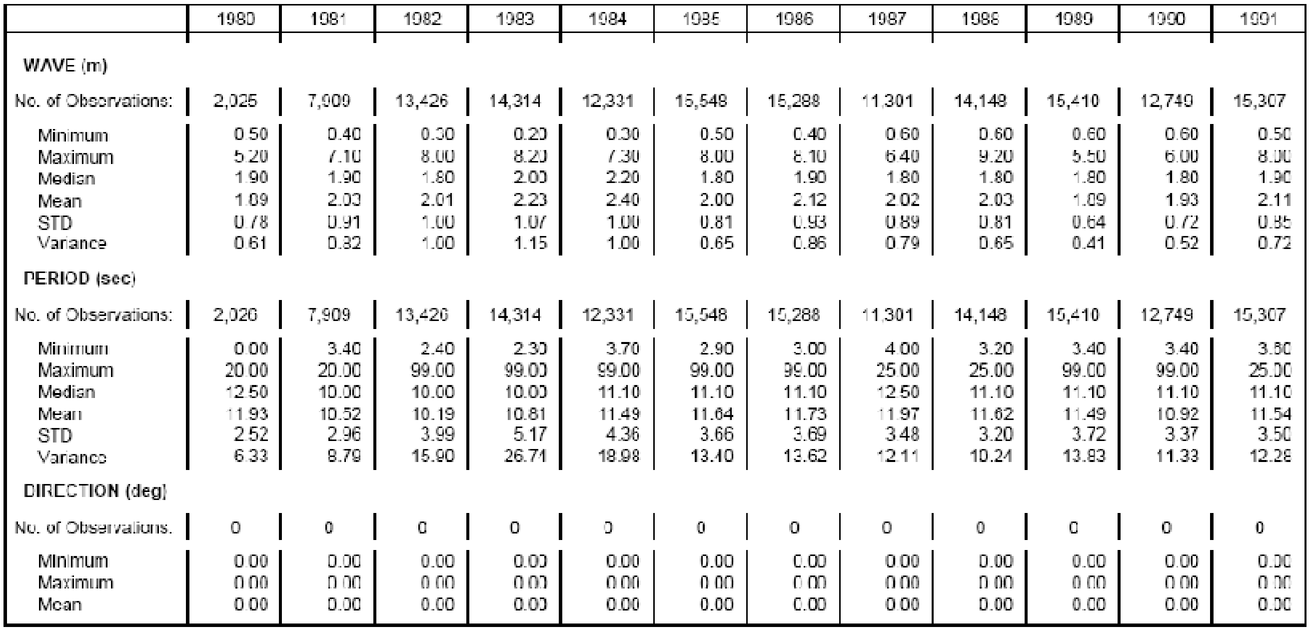


Figure 16. Economic assessment methodology (4).

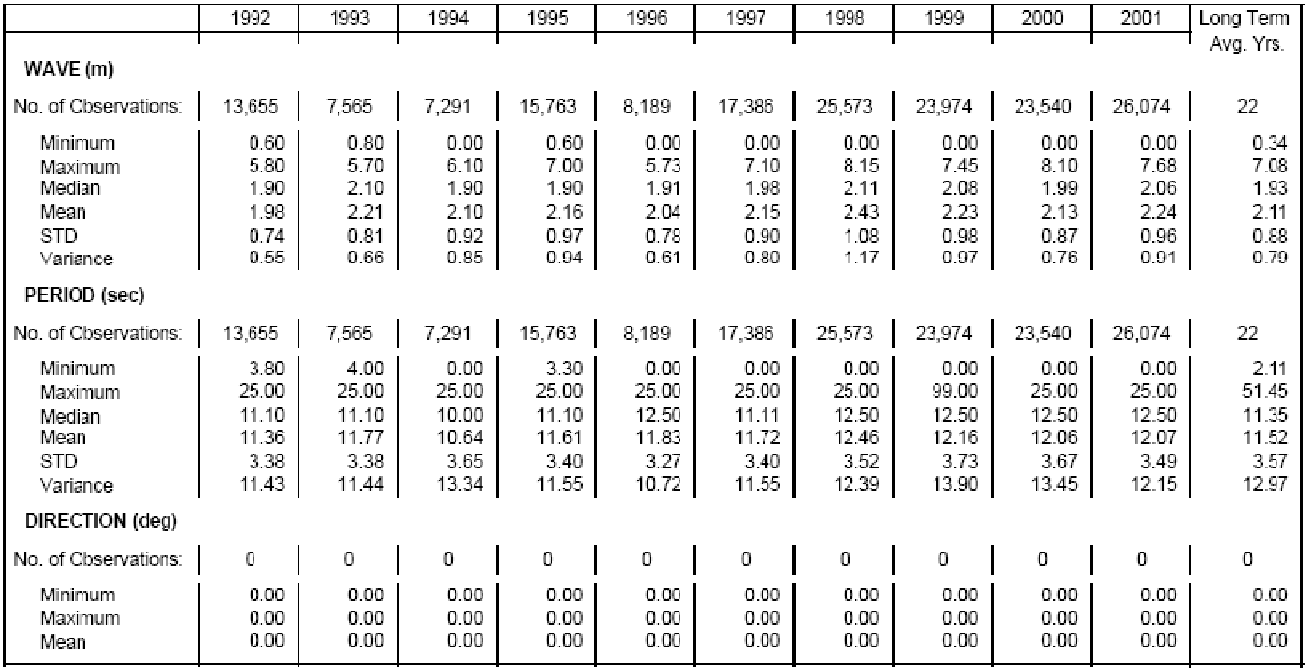
To allow for comprehensive comparisons of economic feasibility between both the Point Arguello and Morro Bay sites, components of all sectors in the methodology flow chart are unique to each site and WEC configuration. Components common between sites and independent of WEC type have been left constant to preserve comparability. Constant parameters for economic assessment are the power plant project life, permitting and environmental mitigations and costs, construction period, financing mechanisms, electrical transmission line losses, expected operational and maintenance costs for each WEC design, insurance costs, and decommissioning costs.

Power Produced

The energy production of each WEC design was calculated at both locations by combining the site specific wave statistics with the WEC power specifications provided by the manufacturer. A formal request for information (RFI) was sent to the 11 manufacturers listed in Table 8. The RFI, included in Appendix B, asked for WEC output as a function of significant wave height (H_s) and peak period (T_p). Of the 11 WEC manufacturers contacted, none of the manufactures provided performance data and the majority declined to respond to the RFI completely. It was gathered that at this point in wave energy industry development, most WEC developers consider almost all design information extremely proprietary and feel that their competitive advantages may be compromised if performance specifications are released. Personal conversation with Stuart Bensley, Board of Directors Chairman of Oceanlinx, kindly confirmed this industry posture and correctly predicted the reluctance of any WEC developer to respond to the RFI. In consequence, WEC device performance specifications were limited to that of published sources and restricted WEC assessment to the AquaBuOY, Pelamis, and WaveDragon WECs. WEC performance specifications were primarily found in *Electricity generation from wave power in Canada* (2008) and *EPRI E21 Offshore Wave Energy Conversion Devices Assessment* (2004). Annual wave statistics were compiled in scatter diagrams for the historical deep water wave statistics for each site, expressing percent occurrence of H_s and T_p energy bins in 0.5 meter wave height and 2.0 second wave period increments. Annual wave statistics for each site were utilized from the 2007 California Energy Commission PIER Report compiled from time deep water-averaged CDIP and NBDC buoy measurements from 1980 to 2001. Annual statistics and number of observations is included in Table 4.



	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
WAVE (m)												
No. of Observations:	2,025	7,909	13,426	14,314	12,331	15,548	15,288	11,301	14,149	15,410	12,749	15,307
Minimum	0.50	0.40	0.30	0.20	0.30	0.50	0.40	0.60	0.60	0.60	0.60	0.50
Maximum	5.20	7.10	8.00	8.20	7.30	8.00	8.10	6.40	9.20	5.50	6.00	8.00
Median	1.90	1.90	1.80	2.00	2.20	1.80	1.90	1.80	1.80	1.80	1.80	1.90
Mean	1.09	2.03	2.01	2.23	2.40	2.00	2.12	2.02	2.03	1.09	1.93	2.11
STD	0.78	0.91	1.00	1.07	1.00	0.81	0.93	0.89	0.81	0.64	0.72	0.85
Variance	0.61	0.32	1.00	1.15	1.00	0.65	0.86	0.79	0.65	0.41	0.52	0.72
PERIOD (sec)												
No. of Observations:	2,020	7,909	13,420	14,314	12,331	15,548	15,288	11,301	14,148	15,410	12,749	15,307
Minimum	0.00	3.40	2.40	2.30	3.70	2.90	3.00	4.00	3.20	3.40	3.40	3.80
Maximum	20.00	20.00	99.00	99.00	99.00	99.00	99.00	25.00	25.00	99.00	99.00	25.00
Median	12.50	10.00	10.00	10.00	11.10	11.10	11.10	12.50	11.10	11.10	11.10	11.10
Mean	11.93	10.52	10.19	10.81	11.49	11.64	11.73	11.97	11.62	11.49	10.92	11.54
STD	2.52	2.96	3.99	5.17	4.36	3.66	3.69	3.48	3.20	3.72	3.37	3.50
Variance	6.33	8.79	15.90	26.71	18.98	13.40	13.62	12.11	10.24	13.83	11.33	12.28
DIRECTION (deg)												
No. of Observations:	0	0	0	0	0	0	0	0	0	0	0	0
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00



	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	Long Term Avg. Yrs.
WAVE (m)											
No. of Observations:	13,655	7,565	7,291	15,763	8,189	17,386	25,573	23,974	23,540	26,074	22
Minimum	0.60	0.80	0.00	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.34
Maximum	5.80	5.70	6.10	7.00	5.73	7.10	8.15	7.45	8.10	7.68	7.08
Median	1.90	2.10	1.90	1.90	1.91	1.98	2.11	2.08	1.99	2.06	1.93
Mean	1.98	2.21	2.10	2.16	2.04	2.15	2.43	2.23	2.13	2.24	2.11
STD	0.74	0.81	0.92	0.97	0.78	0.90	1.08	0.98	0.87	0.96	0.88
Variance	0.55	0.66	0.85	0.94	0.61	0.80	1.17	0.97	0.76	0.91	0.79
PERIOD (sec)											
No. of Observations:	13,655	7,565	7,291	15,763	8,189	17,386	25,573	23,974	23,540	26,074	22
Minimum	3.80	4.00	0.00	3.30	0.00	0.00	0.00	0.00	0.00	0.00	2.11
Maximum	25.00	25.00	25.00	25.00	25.00	25.00	25.00	99.00	25.00	25.00	51.45
Median	11.10	11.10	10.00	11.10	12.50	11.11	12.50	12.50	12.50	12.50	11.35
Mean	11.36	11.77	10.64	11.61	11.83	11.72	12.46	12.16	12.06	12.07	11.52
STD	3.38	3.38	3.65	3.40	3.27	3.40	3.52	3.73	3.67	3.49	3.57
Variance	11.43	11.44	13.34	11.55	10.72	11.55	12.39	13.90	13.45	12.15	12.97
DIRECTION (deg)											
No. of Observations:	0	0	0	0	0	0	0	0	0	0	0
Minimum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Maximum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Mean	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 4. NBDC historical deep water cell statistics 1980 to 2001 (1).

The annual energy production (E_{ave}) of each WEC was then calculated on a monthly basis, per methods used by K. Nielsen in Equation 2, as the sum of the product of the averaged absorbed power (P_{abs}) in each sea state and the number of hours per year this sea state occurs (16).

$$E_{ave} = \sum P_{abs}\,(H_s, T_p) \cdot dt(H_s, T_p)$$ **Equation (2)**

Capital Costs

Wave energy power plants are inherently capital intensive. The harsh marine environment demands more robust systems, as well as specialized operational and maintenance (O&M) techniques. For the purpose of this study, WEC device costs were approximated from available publications and cited accordingly, the majority of which were acquired from Dunnett and Wallace (14). Due to the fact there is minimal industry experience in the actual costs of O & M, rough comparisons may be made from analogous industries, such as offshore oil and gas or offshore wind energy. In this study, both initial installation and O&M costs are either supplied from WEC manufacturers or estimated from relevant studies and cited accordingly. Costs held constant for all site and WEC cases, mentioned previously, are listed in Table 5. A consideration to be emphasized is that the energy source for both sites analyzed, and for all wave energy plants in general, has no cost. Wave energy itself is innately free.

Capital costs included	Capital costs neglected
Site permitting and preparation	Support infrastructure (ships, ports, facilities)
WEC device	Insurance
WEC moorings	Income taxes
Subsea transmission cable	Environmental mitigation
Overland transmission cable	Power synchronization and substations
Project decommissioning cost	Administrative/management costs

Table 5. Economic analysis capital costs.

Operating and Maintenance Costs

Maintenance costs for WECs are expected to be substantial due to the inherent challenges of operating in the marine environment. Seawater is exceptionally corrosive, and the variable loads and shock forces that WECs will be subjected to will require continuous intervention and mitigation. Offshore oil and gas operations have shown that offshore operation and maintenance costs are typically 5-10 times higher than similar onshore activities (2). Survivability and device failure are further issues that will drive up operational costs and necessitate high safety factors and strict tolerances. Historical buoy data shows that significant wave heights of 10 to 11m occur every few years in California waters and WEC devices will incur significant costs and compromises to public safety and the environment should they fail during an extreme wave event (2). Operation and maintenance costs for this study were acquired for the AquaBuOY, Pelamis, and WaveDragon WECs from Dunnett and Wallace and are expressed in terms of cost per kilowatt hour of electricity produced.

LCC and COE Calculation

The LLC and COE were chosen to provide a means of comparison between sites and WEC configuration, as well as determine economic feasibility in relation to the present market COE. The methodologies used were adapted from Dunnett and Wallace and Szonyi et al, and are relatively straightforward. 2009 US Dollars (USD) were used for all monetary calculations. The complete 25-year, 25 MW wave power plant life-cycle cost (*LCC*), at net present value, is calculated as stated in Equation 3 and expressed in 2009 USD. Total power plant capital costs (*CC*), total operating and maintenance costs (*OC*), and total revenues (*R*), are all also expressed in USD.

$$LCC = CC + OC - R \qquad \textbf{Equation (3)}$$

Capital costs are calculated as stated in Equation 5. q represents the number of WEC devices in the wave power plant, and D is the cost of one single WEC device in USD. The cost of mooring lines (c_{ML}), cost of subsea underwater transmission cables (c_{UW}), and cost of overland transmission cables (c_{OL}) are expressed in terms of USD/km. The distance to be covered by underwater transmission cables (d_{UW}), overland transmission cables (d_{OL}), and the length of mooring lines per WEC device (l_{ML}) are all expressed in meters. The wave power plant decommission costs (Z), is expressed in USD at net-present value, with consideration taken to compensate for interest to be earned during operational period.

$$CC = q \times [D + (c_{ML} \times l_{ML}) + (c_{UW} \times d_{UW}) + (c_{OL} \times d_{OL}) + Z] \qquad \textbf{Equation (4)}$$

Total operating costs (OC) for the 25-year plant operational period are calculated using Equation 5. Unit operating and maintenance cost (oc), are included in the equation as a function of power produced, in terms of USD per kilowatt-hour ($/kWh). Since wave power plant power outputs will be calculated annually for each site and WEC configuration, the total electricity produced in a year (k) will be used for the OC calculation, in units of kilowatt-hours (kWh). To represent OC as a present net worth value, the term present worth factor ($PWF_{n,}$) is included for a cash flow of (n) years from now, and defined by Equation 8.

$$OC = \sum_{n}^{N} (oc \times k \times PWF_n) \qquad \textbf{Equation (5)}$$

Total wave power plant revenues (R), expressed in USD, are calculated using Equation 6. The price of electricity (P_{elec}) received by the wave power plant is expressed in USD per kilowatt-hour ($/kWh). P_{elec} is susceptible to significant fluctuations depending on market conditions, and the exact value is considered unknown. For the purpose of this study CC and COE will be calculated multiple times using a range of likely P_{elec} values.

$$R = \sum_{n=1}^{N} (P_{elec} \times k \times PWF_n) \qquad \textbf{Equation (6)}$$

The annual discount rate (i_a) is also a percentage and has been set to 4 percent for this study. Equation 7 is used to calculate the present worth factor (*PWF*) at year (*n*).

$$PWF_n = \frac{1}{(1+i)^{[n-1]}} \qquad \textbf{Equation (7)}$$

Equation 8 equates the payback period (*PP*). *PP* is function of the total electricity produced (K) in the 25 year operational period, expressed in kWh. The PP was calculated for a range of P_{elec} values for analyisis, but is set to an assumed reasonable value of 10-years for comparison between projects.

$$PP = \frac{CC}{(P_{elec} - OC)K} \qquad \textbf{Equation (8)}$$

VI. REGULATORY HURDLES

The regulatory environment is a critical component of the project development decision criteria, and as in many other industries, can often be the deciding factor of whether or a not a project is pursued. Highly involved permitting procedures can raise project costs, and permit provisions such as decommissioning costs are critical to the financial planning of a project. The exact capital costs associated with the permitting of a commercial wave power plant are difficult to accurately quantify, and have been estimated for the purposes of this study by comparison to estimates made by Pacific Gas and Electric Company's for their project. Additionally, the existing uncertainty surrounding the logistics and expense of securing permits for wave energy projects has been prohibitive to development for quite some time. Due to the nascent nature of wave energy conversion development in California, until very recently the explicit legal provisions for installing and operating WECs had yet to be determined. Prior to recent the recent surge in interest of harvesting power from ocean waves, numerous regulatory instruments were in place for both the building structures in coastal waters and for the production of electricity, but none specific to renewable marine energy. The following description of the regulatory environment is meant to provide useful information relevant to the viability of wave energy development, but is not necessary directly related to WEC performance or economic projections.

FERC vs. MMS Dispute

Until April 2009, the largest contribution to the regulatory uncertainty regarding the domestic installation of WECs was the initial dispute of jurisdiction between two Federal agencies, the Mineral Management Service (MMS) of the Department of the Interior (DOI) and the Federal Energy Regulatory Committee (FERC) on the area known as the Outer Continental Shelf (OCS). The OCS is the US Territorial Sea area beginning 3 nautical miles offshore of US coastlines and extending out to 12 nautical miles offshore.

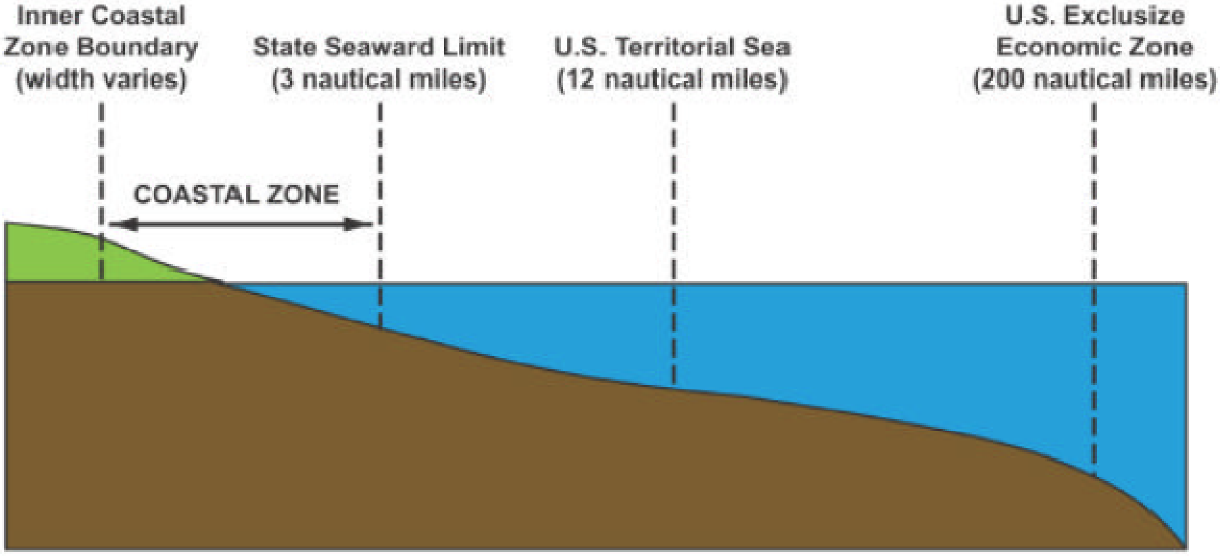


Figure 17. Diagram of coastal regulatory jurisdictions (2).

This discrepancy over permitting *hydrokinetic projects*, a term adopted by the MMS and FERC to describe offshore wave, tide, and ocean current power generating apparatus, was resolved on April 9, 2009 through the issuance of a Memorandum of Understanding (MOU) which described the process by which authorizations related to renewable energy resources in OCS waters will be developed. The basis of the dispute between FERC and the MMS concerns claims to regulatory authority over OCS waters based on opposing Interpretations of the of Part 1 of the Federal Powers Act (FPA) and section 8(p) of the Outer Continental Shelf Lands Act, as amended by the Mandate of Energy Policy Act of 2005 (18). The MMS primarily asserted its jurisdiction based upon the EPAct of 2005, which authorizes the US Secretary of the Interior to issue leases, easements, or Right of Ways on the OCS for activities that support production, transportation, or transmission of energy from sources other than oil or gas (19). FERC countered with provisions from Section 405 and 408 of the Public Utility Regulatory Policy Act of 1978 and other wordings in Part 1 of FPA, which grants FERC exclusive jurisdiction for issuing permits or exemptions for the construction and operation of hydrokinetic projects on the OCS.

A breakthrough in regulatory clarity was recognized on April 9, 2009 when the MOU between FERC and the MMS was published. The agreement outlines provisions now established as law under DOI MMS 30 CFR Parts 250, 285, and 290 Renewable Energy and Alternate Uses of Existing Facilities on the Outer Continental Shelf (Docket ID: MMS-2008-OMM-0012) (18). The regulation is such that hydrokinetic projects on the OCS will be required to secure a MMS lease first, and then will be required to apply for a FERC license before construction or operation of a wave energy power plant commences. The MOU further states that the MMS and FERC will work collaboratively to the greatest extent possible to ensure that OCS hydrokinetic projects follow the public's best interest, and account for adequate environmental protection measures. Both the MMS and FERC also agree to facilitate National Environmental Policy Act (NEPA) analysis necessary for MMS lease and FERC license issuance.

MMS OCS Hydrokinetic Leases

There are two types MMS leases for OCS hydrokinetic projects, limited and commercial leases. Both leases include a project easement for necessary cables or pipelines on the OCS. Limited leases are issued for small scale WEC deployment, testing, and measurement efforts. WECs may be deployed for a short period only if they are considered experimental, and any electricity produced does not displace electricity from or transmit electricity to the interstate electrical grid. Limited leases require a $300,000 bond, $3.00/acre/year rental fee, and are issued for a 5 year term. Commercial leases are issued for 25 year terms, require an initial $100,000 bond for lease issuance, and additional project decommission bonding depending on project size and characteristics. A $3.00/acre/year rental fee is also required as well as a $0.25/acre/year minimum acquisition fee. The rental fee and project bonding are in addition to acquisition fees, which are determined during a competitive sale process. Both limited and commercial leases are issued by the MMS on a competitive basis if competition for hydrokinetic use is deemed to exist for an area of the OCS. Wave energy power plant developers can initiate the competitive lease sale process by submitting an unsolicited request for a lease, or respond to a MMS Request for Interest for an OCS area. The competitive lease process begins when the MMS issues of a Call of Information and Nominations, where the MMS advertisement of the lease sale of the identified area is made public. MMS then accepts bids from interested parties for the use of said OCS lands. If no other interest is expressed, a noncompetitive lease process is initiated. If competitive interest exists for the area, MMS will award the lease to the party with the highest acquisition fee bid, and with the most favorable terms. Additional lease approval processes are then begun, including comprehensive planning approval, environmental assessment and NEPA compliance, and technical feasibility reviews. Once a lease is issued, specific planning benchmarks are required to be met, and MMS reserves the right to scheduled and unscheduled inspections of the leased premises. Decommissioning of structures installed on OCS lands is required at the end of the operational period, and an application stating the intent for structure removal must be submitted to the MMS 2 years prior to removal activities.

FERC Hydrokinetic Licenses

FERC has provisions for the issuance of three types of licensees: preliminary permits, pilot project licenses, and commercial licenses. FERC maintains jurisdiction over all hydrokinetic projects that displace energy from or transmit energy to the interstate electrical grid, whether on the OCS or in state waters. Under the MOU, FERC also will not issue a hydrokinetic license on the OCS until a MMS lease has been obtained first.

Preliminary permits are issued on a “first-come, first-serve” basis, and do not authorize construction, but allow developers to study a project site. During the 3 years that a preliminary permit is valid, the permit holder also gains priority for the site when applying for a commercial license. FERC began accepting applications for preliminary permits in February of 2007 and since has issued 52 preliminary permits for hydrokinetic wave projects.

Pilot project licenses are issued by FERC for short-term testing of experimental technology, and allow for limited grid connection. Pilot projects must be small, have the ability to be quickly shut down or removed, and must include certain environmental safeguards. FERC recently published a Whitepaper describing the pilot project licensing process, and first successfully implemented the process in New York City’s East River with the Verdant Power in-stream tidal project. Commercial licenses for hydrokinetic projects allow for grid connected electrical generation and vary in term length from 30 to 50 years. The licensing process is similar to that of hydroelectric projects, and includes rigorous project plan verification, environmental protections and analysis, and technical review. The only hydrokinetic wave license granted by FERC was by Finavera Renewables for the Makah Bay Offshore Wave Pilot Project, which was awarded on December 21, 2007 and subsequently abandoned on April 21, 2009. No other commercial hydrokinetic licenses have been awarded by FERC since.

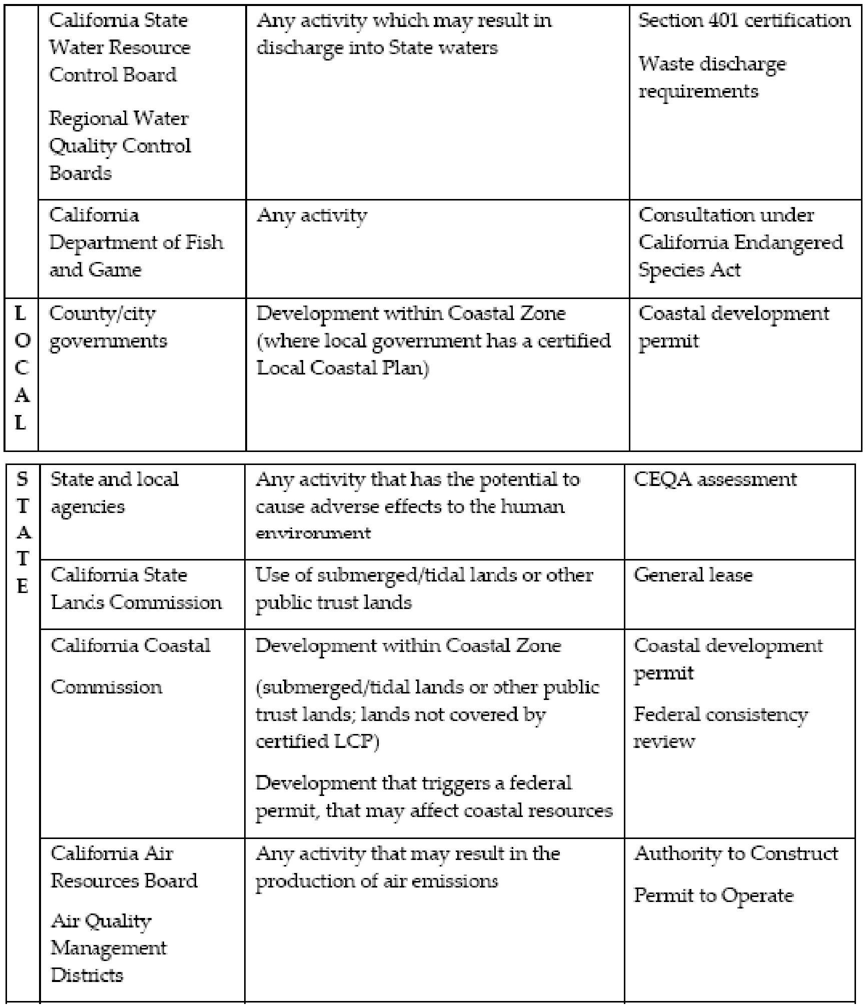
California State Regulations

In addition to the robust Federal permitting process, comprehensive regulatory requirements exist at the state level for the construction and utilization of State ocean waters that would be applicable to a wave energy plant. An assortment of California legislative acts enacted over the years specifically address requirements for projects in State waters. One such piece of legislation is the Submerged Lands Act/ California State Lands Act, which requires a coastal development to be obtained from the California

Coastal Commission before construction on submerged or tidal lands from the mean high tide line out to the 3 mile limit. A list of applicable state regulatory requirements is included Table 6.

Local Governmental Authority

Wave energy power plant installations off the coast of California will likely also require cooperation and approval from local city or county governments for successful construction and operation. Shore side infrastructure surrounding the cable landing, overland electrical, transmission, and operational support systems will all require local governments to administer permits or zoning amendments within their jurisdictions. Such provisions are expected to vary considerably from locality to locality, and the details of such miscellany are outside the scope of this study.



	California State Water Resource Control Board Regional Water Quality Control Boards	Any activity which may result in discharge into State waters	Section 401 certification Waste discharge requirements
	California Department of Fish and Game	Any activity	Consultation under California Endangered Species Act
LOCAL	County/city governments	Development within Coastal Zone (where local government has a certified Local Coastal Plan)	Coastal development permit
STATE	State and local agencies	Any activity that has the potential to cause adverse effects to the human environment	CEQA assessment
	California State Lands Commission	Use of submerged/tidal lands or other public trust lands	General lease
	California Coastal Commission	Development within Coastal Zone (submerged/tidal lands or other public trust lands; lands not covered by certified LCP) Development that triggers a federal permit, that may affect coastal resources	Coastal development permit Federal consistency review
	California Air Resources Board Air Quality Management Districts	Any activity that may result in the production of air emissions	Authority to Construct Permit to Operate

Table 6. State and local government regulatory requirements (2).

VII. FINDINGS AND RESULTS

As the performance and economic modeling was completed for hypothetical wave energy power plants at Sites A and B, every effort was made to accurately capture all parameters pertinent to the realistic commercial deployment of WECs. This task has been successfully achieved; however it must be made clear that the nascent nature of the industry requires that numerous assumptions be made. Assumptions made are identified in their respective categories in the following sections. Further enhancement of this study could be attained by investigating these assumptions further and completing further reiteration of analysis; however the resources available to this study limit its scope to the existing presumptions.

Wave Modeling Results

The historical deep water wave statistics gathered suggested two dominant swell conditions that prevail in the offshore area that encompasses both Sites A and B. CDIP and NBDC buoy data suggest that a swell condition of 3 meter significant wave height, 10 second period, at a 270º direction is typical for winter deep water conditions. Dominant summer deep water swell conditions consist of a significant wave height of 1.75 meters, 10 second period, and 225º direction. These parameters were drawn from conclusions made in the 2007 California Energy Commission PIER Report, and represent statistical time-averages of deep water wave statistics for the coastal zone between latitude 34.300º and 34.3000º. These two wave conditions characteristic of the deep water wave resource in the areas of interest were used as boundary conditions for the shallow water wave propagation computer modeling. Seafloor bathymetry inputs to model were acquired from the file SantaMaria.xyz containing 2436721grid points at an approximate 90 meter rectangular grid resolution. SWAN runs were executed for the coastal areas relevant to Sites A and B and propagate swells from 600 and 800 meters of depth to shore at Sites A and B, respectively. Color plots were created using the program Matlab to illustrate the SWAN output data files. Plots were produced that illustrate significant wave height, peak wave period, swell direction, water depth, and wave energy flux.

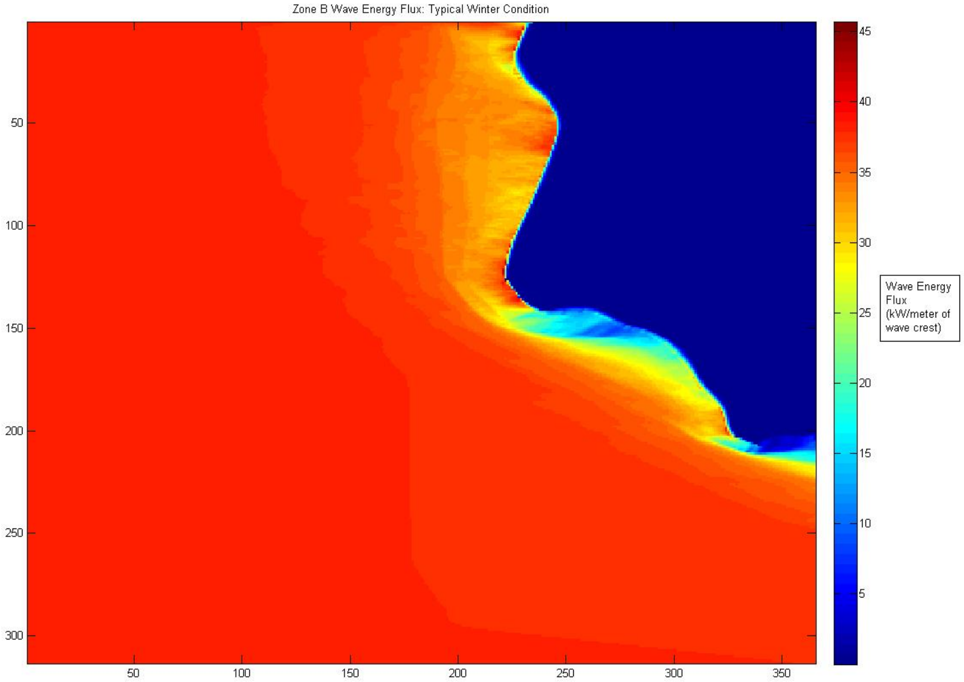


Figure 18. Wave energy flux at Site B during typical winter swell conditions.

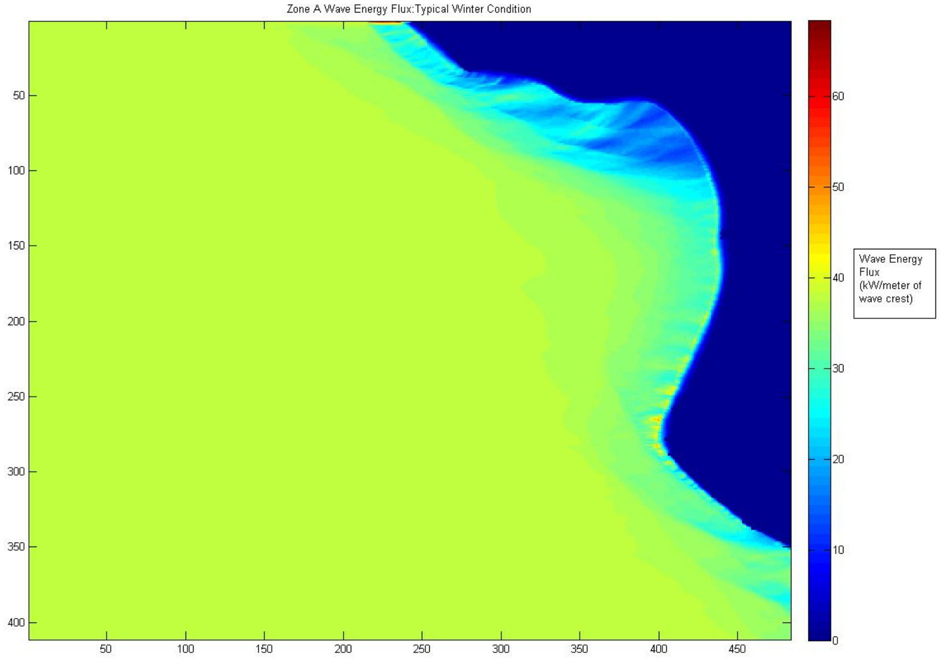


Figure 19. Wave energy flux at Site A during typical winter swell conditions.

Wave energy flux was calculated by running a Matlab command file that utilized significant wave height, peak period inputs, and the calculation methodology described by Equation 1. Plotted results are included displayed in Figures and show interesting results. Consistent with CEC PIER Report findings, Site B exhibited slightly higher wave energy flux in winter conditions, a result of the quickly increasing water depth directly off of Point Conception. However, blockage from Point Conception to south of Site B contributed to the slightly lower summer energy flux due to the southwestern swell direction. Site B displayed winter wave energy densities in the 33-37 kW/m range and summer energy fluxes of 10-12 kW/m. Comparatively, under the same deep water swell parameters, Site A displayed summer wave energy densities ranging from 12-14 kW/m and winter values ranging from 30-35 kW/m. Cross-sectional analysis of the depth contours through both sites also produced interesting results when wave energy flux was plotted as a function of depth. Figures 18 and 19 display wave energy flux values calculated at depths from 200 meters to shore at Sites A and B.

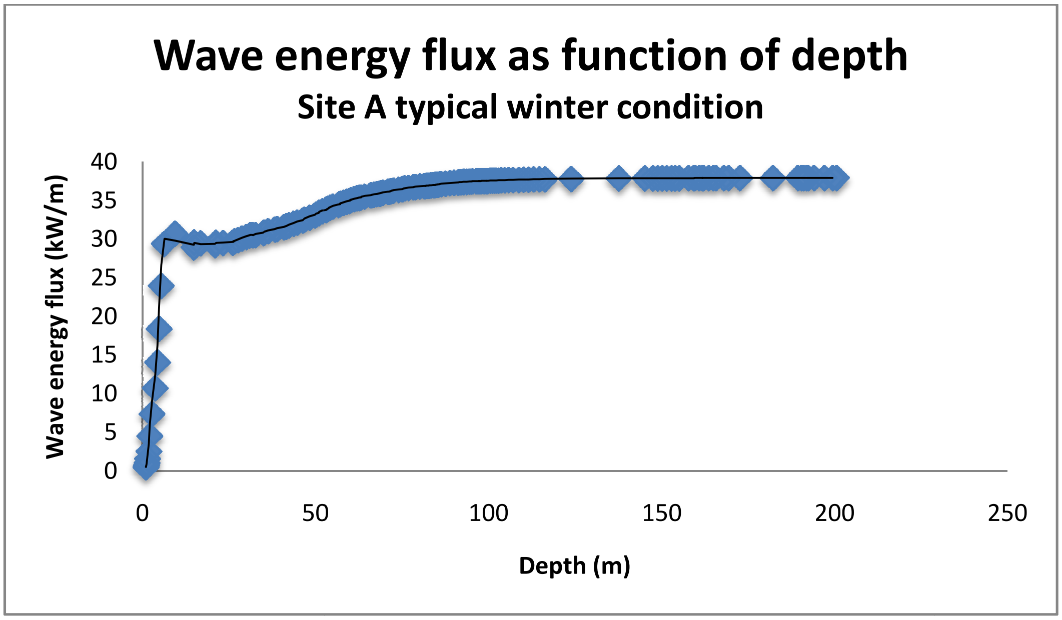


Figure 20. Energy flux calculated at depths from 200m to shore at Site A.

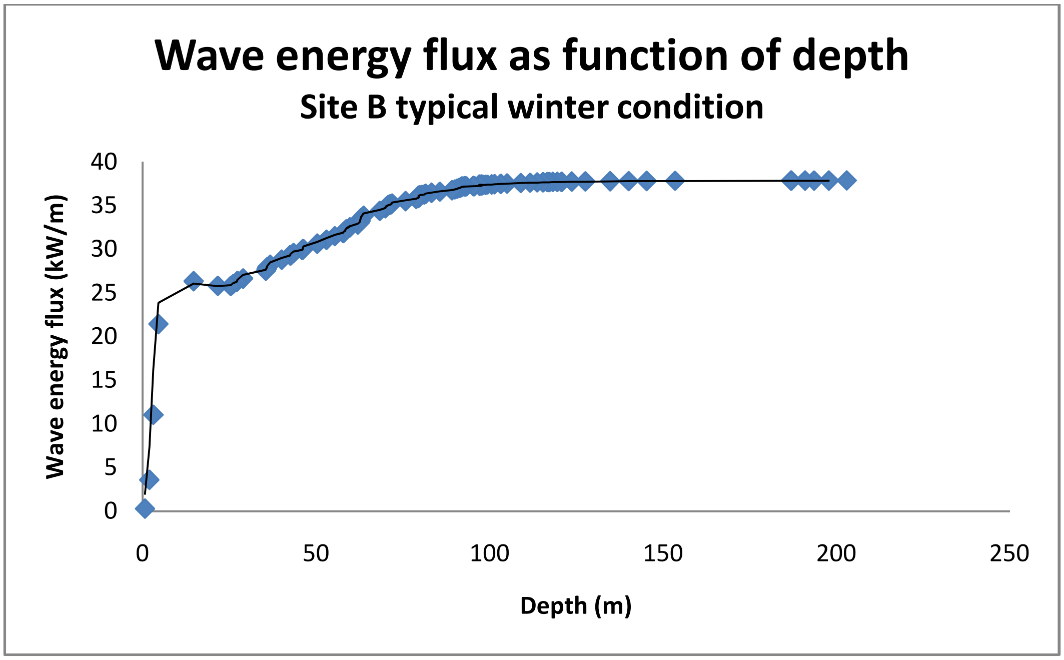


Figure 21. Energy flux calculated at depths from 200m to shore at Site B.

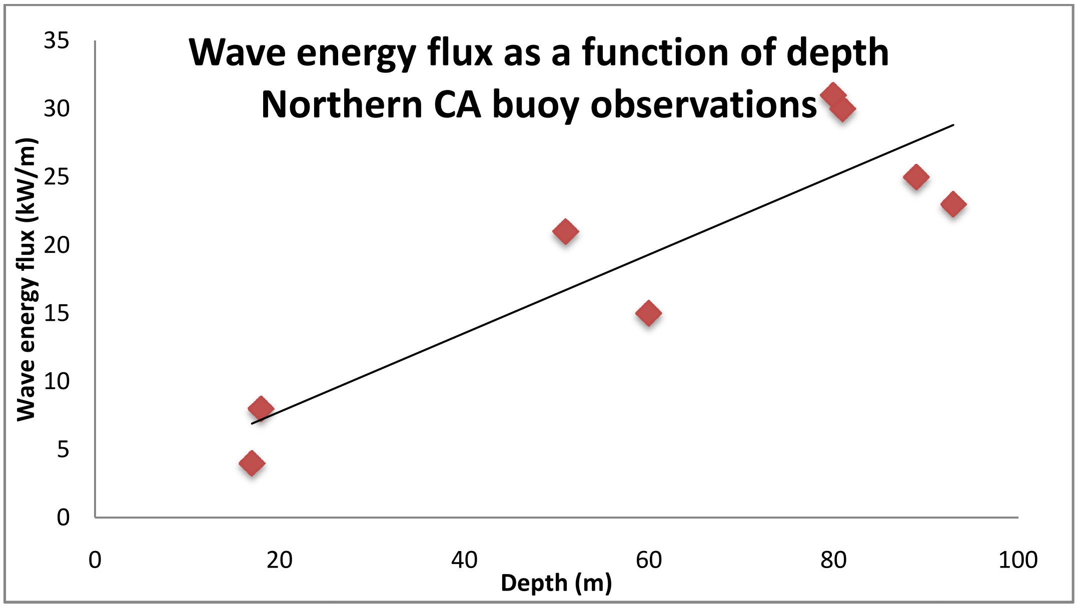


Figure 22. Wave energy flux as a function of depth measured at observation buoys in Northern CA (1).

At both sites, the frictional effect of the seafloor is apparent in the decrease of wave energy flux beginning just below the 100m depth contour. These plots highlight the optimal depth for WEC deployment, at the 80 to 100m depth contour, to minimize wave energy dispersion due to interaction with the seafloor and to maximize cost savings by operating in greater depths than necessary. Sites A and B are reasonably near this optimal depth, and all three WECs included in this study are designed to operate in this range. SWAN model results indicate that at depth greater than 100m the wave energy density does not increase further with increased water depth and in the cases of the Site A and B typical winter swell conditions, and levels off at about 38 kW/m.

The effect of depth on wave energy flux illustrated in Figures 18-19 is supported by a collection of shallow water buoy measurements provided by Previsic and Wilson, et al. (1). Wave energy flux measurements for buoys at a variety of depths experiencing equal wave parameters exhibit significant losses below the 100m contour. These observations, illustrated by Figure 20, vary slightly in respect to the linearity of the relationship compared to that of the modeled data. Due to the multiplicity of variables influencing wave parameters at a particular location, comparisons of observational data from a variety of locations must be used with caution. Extraneous variables such as seafloor frictional coefficients and local bathymetry influences consequently dictate that such observations be used as a general indicator of the shallow water wave energy availability, which generally agrees with SWAN model predictions.

WEC Performance Modeling Results

Due to the findings of the shallow water wave propagation models, it was assumed that for the scope of this study, historical deep water wave statistics supplied by the 2007 CEC PIER report for the study area containing both sites A and B were adequate for the calculation of annual WEC power output. The differences in wave energy density between Sites A and B, as well as the site depths considered to experience near negligible wave energy losses from bottom friction, permit the use of deep water wave statistics within tolerable degrees of uncertainty. Deep water wave statistics compiled from 1980 to 2001 and summarized in Table 7 were compiled into H_s and T_p bins in increments of 0.5m H_s and 2 second T_p.

Tp(sec)

Hs (m)	**0-2**	**2.1-4.0**	**4.1--6.0**	**6.1-8.0**	**8.1-10.0**	**10.1-12.0**	**12.1-14.0**	**14.1-16.0**	**16.1-18.0**	**18.1-20.0**	**20.1+**	**Total**
0.0-0.5	8.76	0	0	0	0	0	8.76	8.76	8.76	0	0	35.04
0.5-1.0	0	8.76	26.28	35.04	140.16	43.8	52.56	87.6	35.04	0	0	429.24
1.0-1.5	0	0	148.92	236.52	665.76	227.76	236.52	306.6	201.48	26.28	0	2049.84
1.5-2.0	0	0	113.88	455.52	709.56	289.08	324.12	262.8	166.44	35.04	0	2356.44
2.0-2.5	0	0	17.52	341.64	438	219	297.84	236.52	113.88	35.04	0	1699.44
2.5-3.0	0	0	0	105.12	236.52	113.88	201.48	201.48	78.84	26.28	0	963.6
3.0-3.5	0	0	0	17.52	122.64	52.56	96.36	175.2	78.84	17.52	0	560.64
3.5-4.0	0	0	0	0	52.56	26.28	52.56	113.88	61.32	8.76	0	315.36
4.0-4.5	0	0	0	8.76	17.52	17.52	26.28	52.56	43.8	8.76	0	175.2
4.5-5.0	0	0	0	0	8.76	8.76	8.76	26.28	26.28	8.76	0	87.6
5.0-5.5	0	0	0	0	0	0	8.76	8.76	17.52	8.76	0	43.8
5.5-7.0	0	0	0	0	0	8.76	0	8.76	26.28	0	0	43.8
7.0-9.0	0	0	0	0	0	0	0	0	0	0	0	0
9.0-11.0	0	0	0	0	0	0	0	0	0	0	0	0
											TOTAL	**8760** hours per year

Table 7. Historical deep water wave scatter plot bins displaying hours of occurrence per year.

WEC performance specification scatter diagrams presented in Appendix D were fit to the deepwater wave resource data and the expected annual power output for each device was calculated according to Equation 2. WEC manufacturer specifications were made to fit the wave resource scatter diagram though several means. In the case of Pelamis, performance specifications were given in terms of T_{Power}. T_{Power} was converted to T_P using the conversion $T_{Power} = 0.9T_P$, as done by Dunnett and Wallace (14). In the case of Wave Dragon and Finavera, T_P bins were merged to fit the wave resource scatter diagram bin widths. Device capacity factors were also calculated and the results are included in Table 8. Capacity factor is defined as the percentage of time the WEC operates at its rated capacity. Spreadsheets used in WEC performance calculations are included in Appendix D.

WEC	Annual power output (kWh)	Capacity factor (dimensionless)
AquaBuOY	374100	0.17
Pelamis P1	1177100	0.18
WaveDragon	7428900	0.12

Table 8. Annual WEC power output and capacity factor.

Economic Analysis Results

The net present value (NPV) of the 25-year project life-cycle (LCC), internal rate of return (IRR), and payback period were computed for prices of electricity ranging from $0.04 to $0.30 per kilowatt-hour. Cash flow computations were calculated yearly for a 25-year project life using Microsoft Excel spreadsheets. NPV, IRR and payback period results were plotted as a function price of electricity, and trend lines were added to identify rates of change when available. Examples of calculation sheets and all plots are included in Appendix E for reference. Due to the fact that no commercial wave energy plants with capital operational cost experience, several assumptions were made that limit the certainty of the performed economic analysis. Two of such assumptions likely to have a significant effect on the comparative advantage of sites A and B regard the travel distance to an industrial deep water port, and the full installation cost of the subsea cable. All other cost parameters are listed for each WEC at both sites in Appendix E.

Distance to Industrial Port

For the purposes of this study, it was deemed sufficient to assume that operation and maintenance costs would be identical for both sites with respect to each WEC design. Operation and maintenance cost estimates were calculated as a function of electricity (kWh) produced, are included in cost analysis spreadsheets contained in Appendix E, and were acquired from values published by Wallace and Dunnett (14). A significant contributing factor to the maintenance cost of a commercial wave energy plant is expected to be attributed to downtime and fuel costs associated with WEC device transportation to a haul out facility. Both Site A and B have intermediately sized harbors in the immediate vicinity, Morro Bay Harbor in the Case of Site A, and the Vanderberg Air Force Base harbor in the case of Site B. These harbors would likely be adequate for support vessels such as medium sized tugs and crew boats with drafts up to 5 meters. However, the deployment and haul out of WECs will likely require a deeper, industrial harbor that can accommodate the draught of WECs such as the AquaBuOY, which draws 30m in its vertical position. The nearest such harbor is the Port of Hueneme, located in Ventura County. Site B is approximately 155 kilometers traveling distance from Port Hueneme, while Site A is approximately 85 kilometers further North, and 245 kilometers traveling distance from this deep water port. This added distance will likely increase maintenance costs at Site A, but the magnitude of such increase would be highly dependent upon maintenance schedules that have yet to be determined.

Subsea Cable Costs

A unique attribute of Site B is the close proximity to a variety of existing infrastructure related to the offshore oil and gas industry. It is assumed that the existing subsea cables or pipelines could be refitted for the transmission of electricity from the wave energy plant at Site B to shore. This assumption is was confirmed during independent communication with industry experts, and would reduce the capital costs of a wave energy project substantially. Surveys of current subsea cable technology provide an expected cost of $102,500 per km for installation of a cable capable of transmitting 25MW of power. The savings of reducing the distance necessary to install new cable is an estimated $745,000 and is included in the cost analysis spreadsheets included in Appendix E.

Other Cost Parameters

To accurately depict the economic life-cycle of each site, several financial instruments were utilized. It can be expected that a significant decommissioning expense will be required at the end of the project life. For this study, it was assumed that $100,000 would be an adequate cost for the removal of each installed WEC. It can also be assumed that decommissioned WECs would retain a certain salvage value at the time of their removal. This study assumed that each WEC would retain 15% of its initial capital investment cost after completion of its 25 year service life. To prepare for the required end of project life expenditures, a sinking fund was implemented to accrue the necessary capital. Equal annual payments were subtracted from annual revenues to account for the end of life expenditures occurring at the end of year 25. In the case of Pelamis and WaveDragon, the WEC salvage value exceeded decommissioning costs, and the difference was added to year 25 revenue.

Additionally, mooring costs were calculated as a function of site depth and WEC design specification. Mooring chain was estimated to be $20/meter, and a mooring scope of 3:1 was assumed for slack moored mooring systems.

Overland transmission cable costs were neglected due to the close proximity of utility grid connection points. Site A is directly adjacent to the Morro Bay natural gas power plant which provides a high capacity grid connection. Site B has nearby access to high capacity power lines supplying Vanderberg Air Force Base, which are operated by the utility Pacific Gas and Electric. Due to the close proximity of these connection points, it can be assumed that the capital costs of additional overland transmission cables are negligible.

Site A Results

Several indicators of economic viability of wave energy plants at Site A are plotted on in the following Figures 21-23. The net present value indicator is used to gauge the worth of the project LCC over its expected life in 2010 US dollars. The AquaBuOY demonstrated a positive NPV LCC at of P_{elec} $0.11/kWh, the lowest price of electricity of the three WECs. Pelamis required the highest electricity prices, requiring a P_{elec} of $0.19/kWh to provide a positive NPV LCC. WaveDragon required a $0.16/kWh to produce a net positive investment.

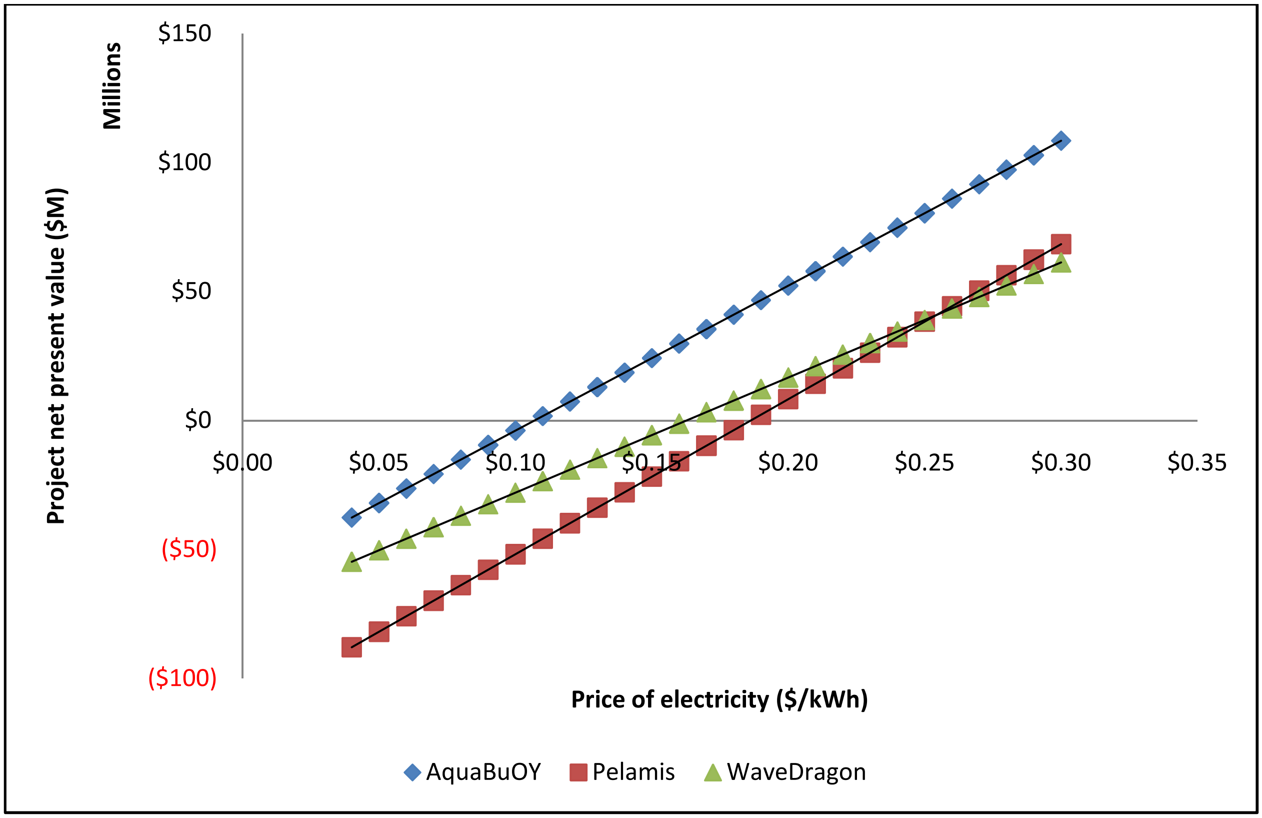


Figure 23. Net present values of 25 year project at Site A as function of the price of electricity.

The internal rate of return is a significant indicator of project profitability, when used in conjunction of net present value to determine not only the total value of the capital investment over the project life-cycle, but is also useful for comparison with other investment options. The annual interest rate was assumed to be 4%, and at Site A the AquaBuOY exceeded that value for prices of electricity above $0.11/kWh. Economic analysis of Pelamis and WaveDragon at Site A found that electricity prices of $0.19/kWh and $0.16/kWh provided an IRR of 4%.

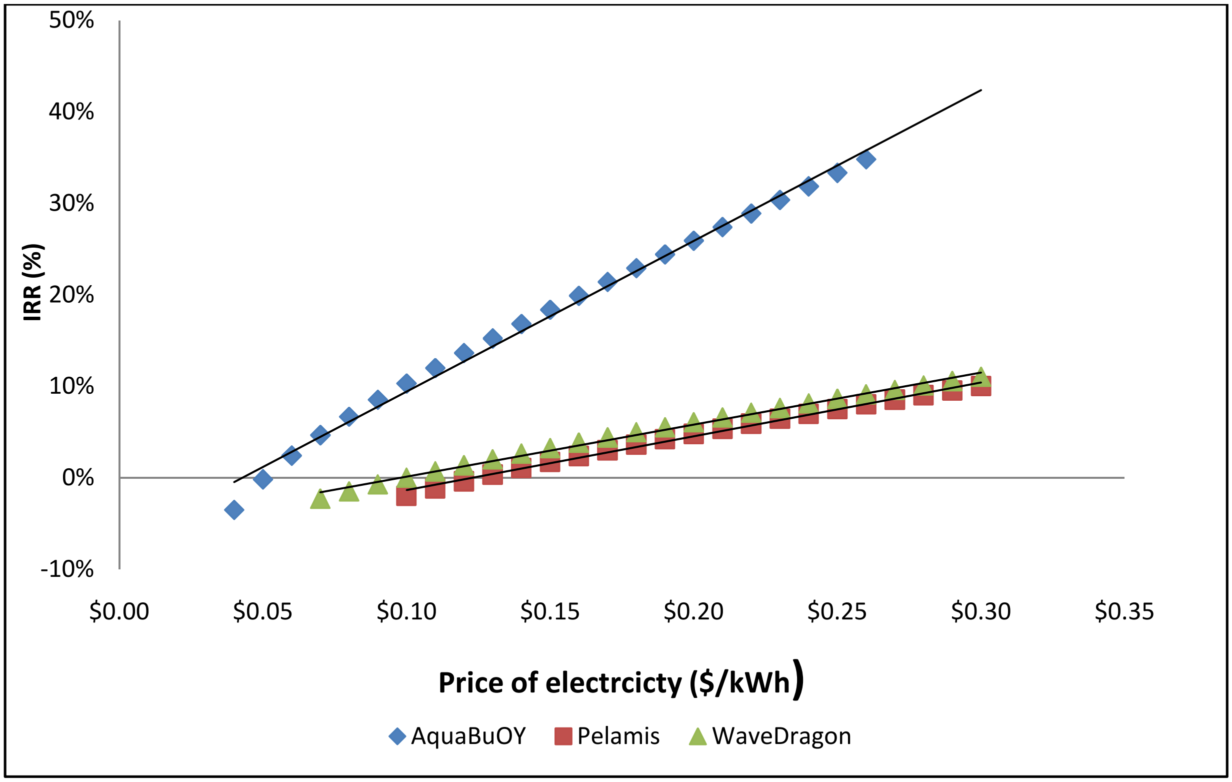


Figure 24. Internal rate of return for Site A as a function of the price of electricity.

The payback period for capital investment in a 25-year operation lifecycle of commercial wave energy plant at Site A decreased quickly as prices of electricity increased, however the AquaBuOY again provided favorable results in comparison to Pelamis and WaveDragon. For a standard 10-year payback period, AquaBuOY required $0.13/kWh in comparison to $0.28/kWh and $0.26/kWh for Pelamis and WaveDragon, respectively. The payback period for AquaBuOY leveled off near 4 years for electricity prices greater than $0.20/kWh. Pelamis and WaveDragon payback periods did not level off until $0.26 - 0.28/kWh, and did not breach payback periods less than 9 years for any electricity price analyzed. The payback period at Sit A as a function of price of electricity is plotted in Appendix E.

Site B Results

Economic indicators of profitability were slightly more optimistic at Site B in comparison to Site A due to slightly discounted capital costs provided by existing infrastructure and the decreased water depth. The savings attributed to subsea cable averaged $744,000 in capital costs for each project at Site B. Site B produced the lowest required price of electricity for a 10-year payback period with the AquaBuOY at $0.13/kWh. NPVs of all three WECs were similar to that at Site A, however the rate at which the NPV of AquaBuOY and Pelamis projects increased was observed to be nearly identical, and significantly greater than the rate at which the NPV of WaveDragon increased in relation to corresponding increases in the price of electricity. At $0.25/kWh and greater, Pelamis retains a greater NPV LCC, however for electricity prices less than $0.25/kWh, WaveDragon provides for a greater NPV second only to the AquaBuOY. The 25-year project life-cycle NPV is plotted as a function of the price of electricity in Figure 23 for each WEC configuration.

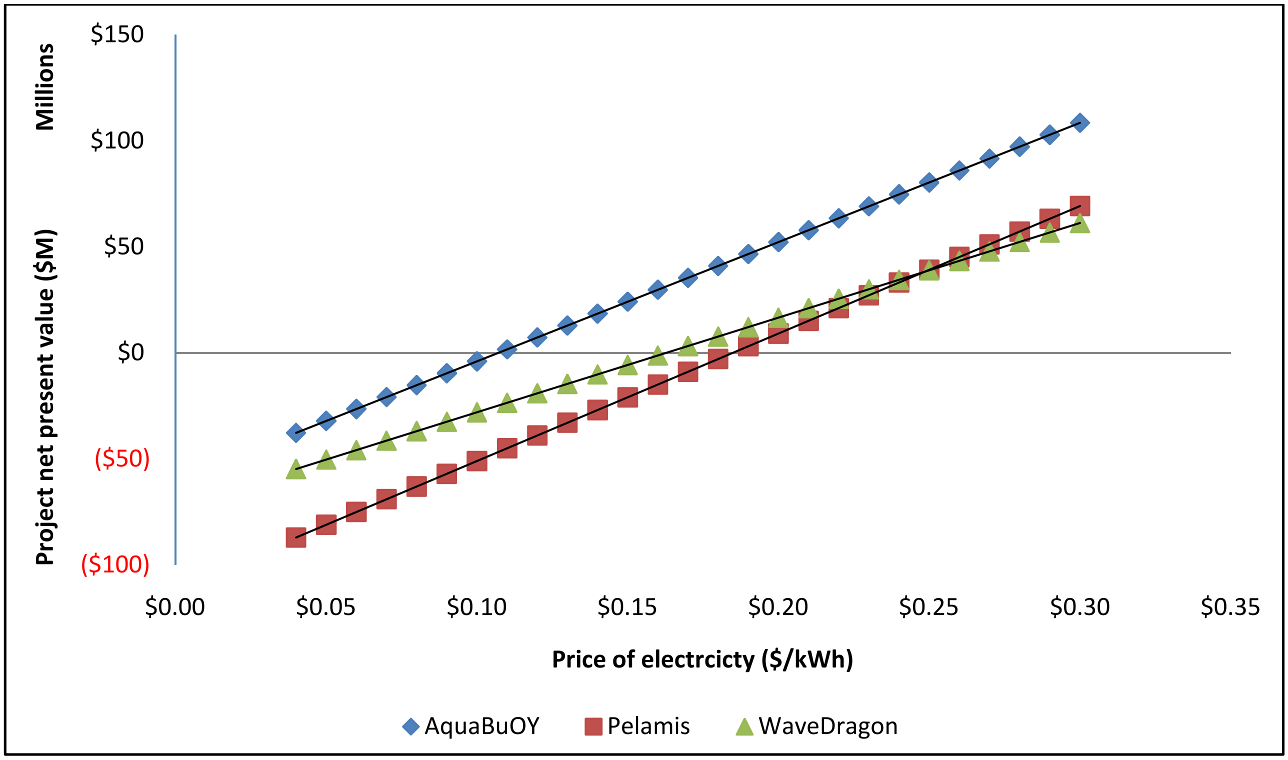


Figure 25. Net present values of 25 year project at Site B as function of the price of electricity.

The internal rates of return for 25MW wave energy plants over a 25-year project life-cycle were slightly higher than those at Site A, and for all three WECs the IRR increased more rapidly with increased prices of electricity than of Site A. As in the case of Site A, the relationship between project IRR and price of electricity demonstrated a linearly positive correlation. Again the AquaBuOY provided an IRR equal to the annual interest rate of 4% at electricity prices far below Pelamis and WaveDragon. The AquaBuOY provided an IRR of 4.00% at \$0.11/kWh, while Pelamis required \$0.18/kWh and WaveDragon required \$0.16/kWh for an equivalent IRR. The plot of IRR as a function of P_{elec} is included in Appendix E for reference. The payback period calculations for Site B were very similar to that of Site A. AquaBuOY again displayed the quickest payback periods throughout the entire spectrum of electricity prices, while leveling off at a payback period of 3-years for electricity prices greater than \$0.29/kWh. Payback periods at Site B of Pelamis and WaveDragon remained \$0.06-0.07/kWh higher for the same price of electricity. The payback period at Site B as a function of P_{elec} is included in Appendix E.

VIII. DISCUSSION

Determining the economic feasibility of the wave energy plants evaluated requires the combination of all three of the economic measures examined and the comparison of results to the current market alternate investments. Due to the significant level of uncertainty associated with the lack of operational wave energy experience, economic projections must be particularly attractive to motivate the necessary capital investments. Current plans for wave energy plant development at Site A by Green Wave Energy Solutions and also at Site B by the Pacific Gas Electric Company encourage favorable projections of investment in wave energy's economic viability. Results from this study support the likelihood of wave energy plant profitability, and also identify several parameters which increase that probability.

Site B proved to demonstrate the most attractive measures of profitability, providing for the lowest P_{ele} required for a 10-year payback period at \$0.13/kWh using the AquaBuOY WEC. Although increased capital costs were required at Site A, the required P_{elec} for a 10-year payback period changed very little, increasing a maximum of only \$0.01/kWh. AquaBuOY consistently provided the most attractive WEC economic projections, while Pelamis and WaveDragon performed similar to each other, yet requiring nearly twice the price of electricity as the AquaBuOY. Nevertheless, the market price of electricity is the benchmark which each proposed project must be judged by.

The US Energy Information Administration (USEIA) compiles statistics regarding the generation and distribution of electrical power in the United States. End of use (retail) prices for all electricity sold in the US averaged $0.098/kWh in 2008 and $0.096/kWh in 2009. 2010 retail prices are projected to average $0.094/kWh in 2010 and increase slightly to $0.099/kWh by 2015. Projections beyond 2015 are considered highly speculative, but project an average 2.1% annual increase in retail electricity prices resulting in prices of $0.171/kWh in 2035 (nominal US dollars) (20). End of use prices in California are several cents higher on average than the rest of the US, and averaged $0.1368/kWh in 2009 and $0.1256/kWh in 2008. However, the price of electricity that a power generation facility receives for the sale of electricity is merely a fraction of what the retail price is at the end of use. The USEIA estimates that on average, 67% of the retail electricity price pays for electricity generation, while the remaining 33% is directed toward the transmission and distribution of power. This assumption would provide a current average wholesale cost of electricity generation in California of $0.09166/kWh.

Although this assumed average is three to four cents per kilowatt-hour less than the required price of electricity for a 10-year payback period, projects using the best performing WECs could be considered profitable if investors accepted a longer payback period and a more modest IRR. Additionally, these figures do not take into account potential subsidies for renewable energy, or the predicted increase in electricity prices over the project lifespan. WEC performance and energy conversion efficiencies are also expected to increase as industry deployment experience accrues, further adding value to future projects. Technology learning curves experienced by the offshore and terrestrial wind, as well as solar industries, provide evidence that industry experience substantially lowers capital and operational costs as the industry matures. Technology learning curves and their associated impact on cost reduction is discussed in detail in the end of this section.

A variable found to be significant to the economic profitability of a wave power plant is the project size. An installed plant peak capacity of 25MW was selected for this study to mirror the initial deployments proposed for commercial development at each site. In some cases, the economy of scale achieved by plant size had a significant impact on project value. The AquaBuOY proved to be the most sensitive to this variable, and rapidly increased in both NPV and IRR measures when the plant capacity was increased. The NPV increased linearly as a function of plant capacity, while the IRR increased in a logarithmic function, increasing rapidly initially and then leveling off at 200MW. The plot shown in Figure 24 illustrates the NPV LCC and IRR relationship with plant capacity at a P_{elec} of $0.0100/kWh, a value that provided a negative NPV when initially modeled at 25MW capacity. This relationship was evident with both other WEC designs, albeit less pronounced. This result should be considered as an import variable in the early stages of plant design, and may dictate the proposal of larger projects in the future. Figure 25 excerpted from a 2009 marine energy industry report in the United Kingdom, independently supports this relationship.

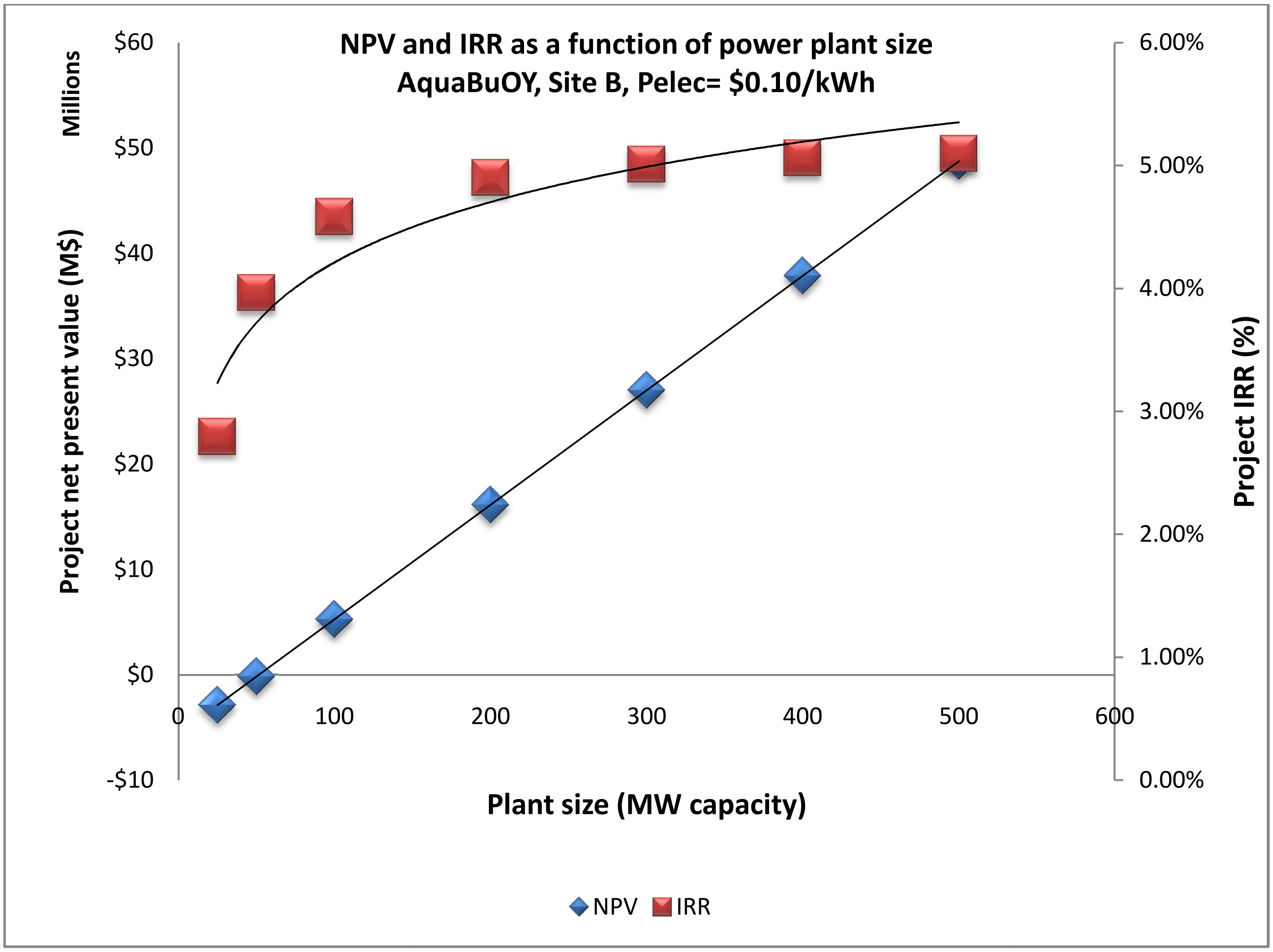


Figure 26. Net present value and internal rate of return as a function of installed plant capacity.

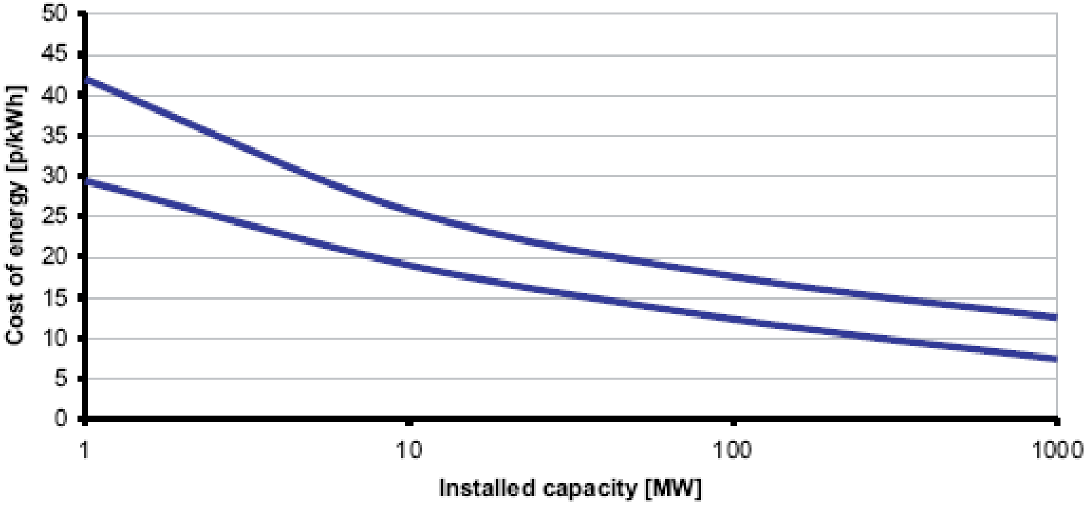


Figure 27. Cost of Marine energy (in British Pounds) as function of installed capacity (21).

Technology Learning –Curves

Technological learning, or learning-curves, are being increasingly utilized to model the future costs of new energy technologies, and their principles may be effectively applied to future projections of the wave energy industry. Learning curve estimates are useful in describing the projected progress of a particular technology as a function of the accumulative experience of an industry. Unit cost reductions are non-linear, and although cost typically does decreases over time, learning curves are a function of accumulative experience. Estimated learning curves for emerging energy technologies are typically being based on non-energy studies, however the historical records of the photovoltaic (PV) industry includes a complete enough data set to be useful for establishing likely outcomes for other renewable energy technologies (21). Over the last 40 years, PV efficiencies have steadily increased and module manufacturing prices have decreased, on the whole following a general trend of a 20% manufacturing cost reduction for every doubling of worldwide production, or a 20% learning-curve (22).

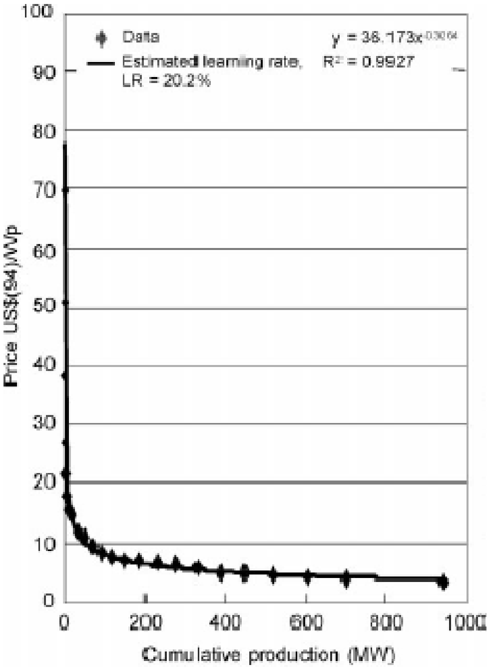


Figure 28. Learning curve estimates for PV unit manufacturing prices (5).

By 2002, the average cost of PV cells was reduced to $2.00 per watt, a 60% reduction over costs only 10 years prior, during which US PV production alone increased sixteen fold (22). The 20% learning-curve historical average achieved by the PV industry is at the upper limit of projected learning rates for emerging energy technologies which range from 16-19% (21). The exceptional technological learning of the PV industry did not occur spontaneously. However, the substantial investment and industry experience accumulated swiftly, and the associated benefits of unit cost reduction became adjusted accordingly.

The technology learning curve is particularly important when determining breakeven points in economic analysis of proposed technologies. The manufacturing capacity required to reach experience levels such that unit cost may be brought down to the competitive cost target is an economic factor that can greatly influence investment decisions. Figure 27 illustrates the sensitivity of learning rates on break even capacity (21). The bars on the left represent break even capacities for a hypothetical emerging energy technology with initial capital cost of $2000/kW and a target unit price of $1000/kW. Break even capacity is the capacity additions needed to drive unit cost down to the specified target cost The bars on the right represent investment capital required to reach the specified target cost. As illustrated by Figure 27 the significance of small variations in the learning rate can greatly alter required break even capacities and technology maturing costs. In this example, an increase in learning rate to 20% from 10% would decrease technology maturing costs from $16 billion to $2 billion, and reduce the break even capacity from 96GW to 9GW (21).

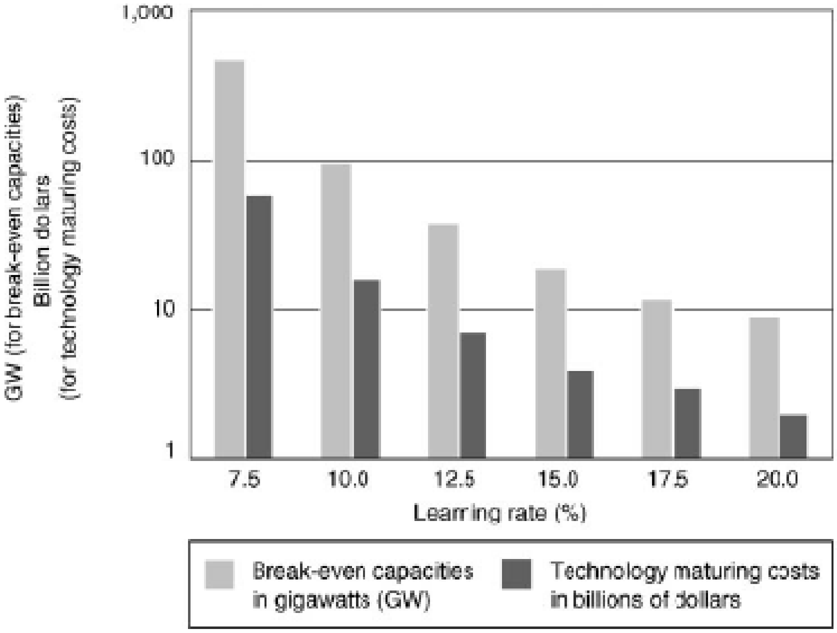


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Figure 29. Sensitivity of break even capacities and technology maturing costs to learning curve variations (21).

The technological learning of the PV industry can be analogously compared to the future of wave energy with several caveats. Principally, the majority of cost reductions achieved in the last 40 years of PV industry experience are derived from innovations in the silicon wafer production processes, a significant cost contributor to PV installations. In comparison, most WEC production processes are derived from well established off the shelf technologies borrowed from various marine applications. The potential for large cost savings in the production of WECs comes from efficiencies of scale and mass production, but most likely not due to significant production process innovations. The areas that may present the greatest opportunity for WEC installations to capitalize on technological learning are device survivability and part-load efficiency. As industry experience is earned, operation and maintenance costs will likely be reduced due to improved WEC dependability, and WEC performance will surely increase.

Specifically, there is great room for improvement of WEC performance efficiencies in part-load conditions. Due to the high variability of incident wave direction, frequency and height, WECs must efficiently accommodate a whole spectrum of sea conditions. Beyene and Wilson detail the mechanics of the variable loads imposed on WECs during operation, and the highlight the power take off as a critical contributing component to the overall WEC energy recovery rate (12). The inherent discrepancy with rated kW capacity and actual average power output of installed WECs is highly dependent on the local deployment location conditions, as well as seasonal variations. As demonstrated by the low capacity factors calculated in this study, ranging from 12.1-17.9%, inefficiencies greatly increase when sea conditions fall outside of the design region of the WEC. All three WECs in this study have a limited ability be tuned to local conditions, and the efficiency improvements of such which have not been discussed in this study. However, the improvements in the ability to increase WEC capacity factor is an area in which industry technological learning has a significant opportunity to improve.

Additionally, it is worth the mention that WECs present the potential to be coupled with other technologies, such as desalination, to increase functionality and investment value. Some emerging WEC designs such as the CETO, a WEC produced by Renewable Energy Holdings, are easily converted to be utilized for reverse osmosis desalination. Pressurized seawater that is normally driven through a turbine to run a generator is diverted to a system of membranes that purifies seawater. Adaptations such as this allow for the flexibility to create value in a variety of markets.

IX. CONCLUSION

Both Morro Bay and Point Arguello sites proved show promise for commercial development of wave energy conversion. The wave energy flux at each location was calculated using SWAN software and 21-years of historical deep water wave statistics. Modeling predicted a wave energy flux of 30-35 kW/m for the typical winter wave climate at Site A, and 12-14 kW/m in the typical summer wave conditions. Site B was modeled to exhibit a wave energy flux of 33-37 kW/h in identical typical winter conditions and 10-12 kW/m in summer conditions.

Wave energy converter device performance was executed by matching statistical time-averaged bins of wave height and period conditions with WEC performance specifications. The WaveDragon WEC produced the highest annual power output, at 7,429,000 kWh, while the Pelamis P1 WEC exhibited the highest capacity factor, producing a full rated capacity of 750 kW 18% of the year.

The lowest necessary price of electricity identified that a commercial wave energy powered electricity generating facility required, at an installed capacity of 25 MW, was $0.1300/kWh to provide a 10-year payback period over the plant's 25-year expected lifecycle. This project utilized the Finavera AquaBuOY at Site B, near Point Arguello, California. The associated internal rate of return on the $24,343,000 initial capital investment was calculated to be 9.05%, creating a net present project value of $13,971,000. The WaveDragon and Pelamis WECs performances were less favorable, requiring $0.2600/kWh and $0.2800/kWh respectively, for identical installed capacities, expected project life lifecycle, and payback period. Site A, near Morro Bay, California proved to require slightly higher capital costs, however required prices of electricity were within $0.005/kWh of Site B for all WECs analyzed. Installed plant capacity was revealed to be an important variable in the economic viability of each project, and installed capacities of 150-200MW are likely to optimize investment efficiency.

Required prices of electricity to be paid to a 25 MW wave energy plant at either site generating electricity using the best performing WEC considered are $0.04/kWh more than current average wholesale costs of electricity generation in the State of California. At this time, wave energy projects could achieve economic viability at either location if the slightly higher electricity costs were accepted by utilities motivated to incorporate renewable energy into the grid, or if other regulatory incentives encourage development of California's wave energy resource. Furthermore, the inclusion of anticipated increases of wholesale costs of electricity and the cost reductions created by technological learning of the wave energy industry produced relatively conservative 25-year plant lifecycle cost estimates.

Proposed wave energy developments on the central California coast will confirm by experience the economic viability of such projects if and when they materialize, however projections from this study predict that such an investment would be attractive if any of the previously stated conditions were met. Additionally, non energy applications such as desalination could potentially couple with wave energy conversion to further increase the investment value of wave energy projects.

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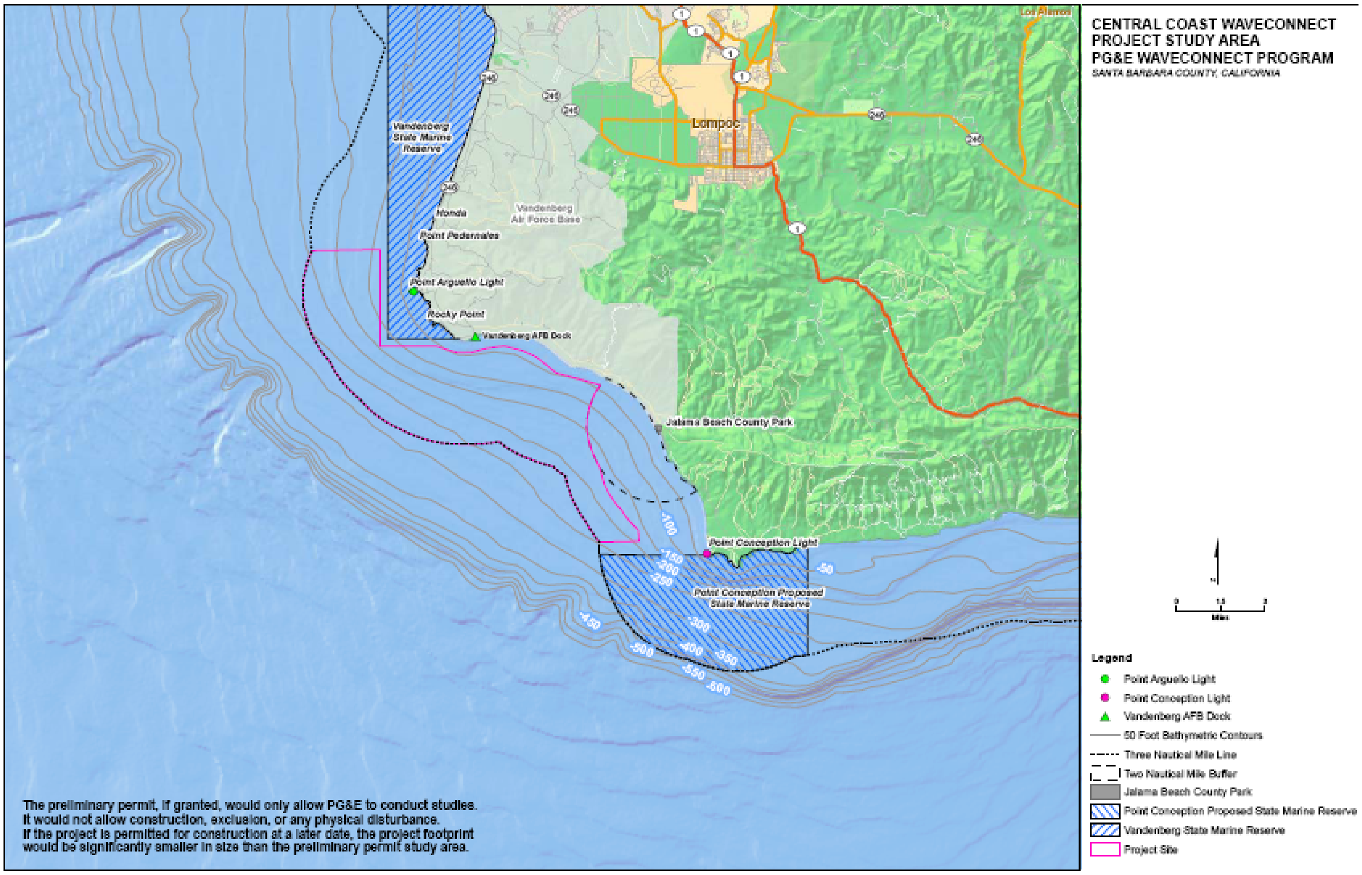
APPENDIX A: PROPOSED COMMERCIAL PROJECT DETAILS



The preliminary permit, if granted, would only allow PG&E to conduct studies.
It would not allow construction, exclusion, or any physical disturbance.
If the project is permitted for construction at a later date, the project footprint would be significantly smaller in size than the preliminary permit study area.

Figure 30. Pacific Gas and Electric Company Central Coast WaveConnect™ project map.

Permit status	Project capacity	Approximate size of project area	WEC manufacturer specified	Proposed date of construction
Pending FERC preliminary permit application, submitted 12/11/2009	10MW initial, eventual 100MW	48 nautical square miles	Not yet identified	2012

Table 9. Pacific Gas and Electric Company Central Coast WaveConnect™ project details.

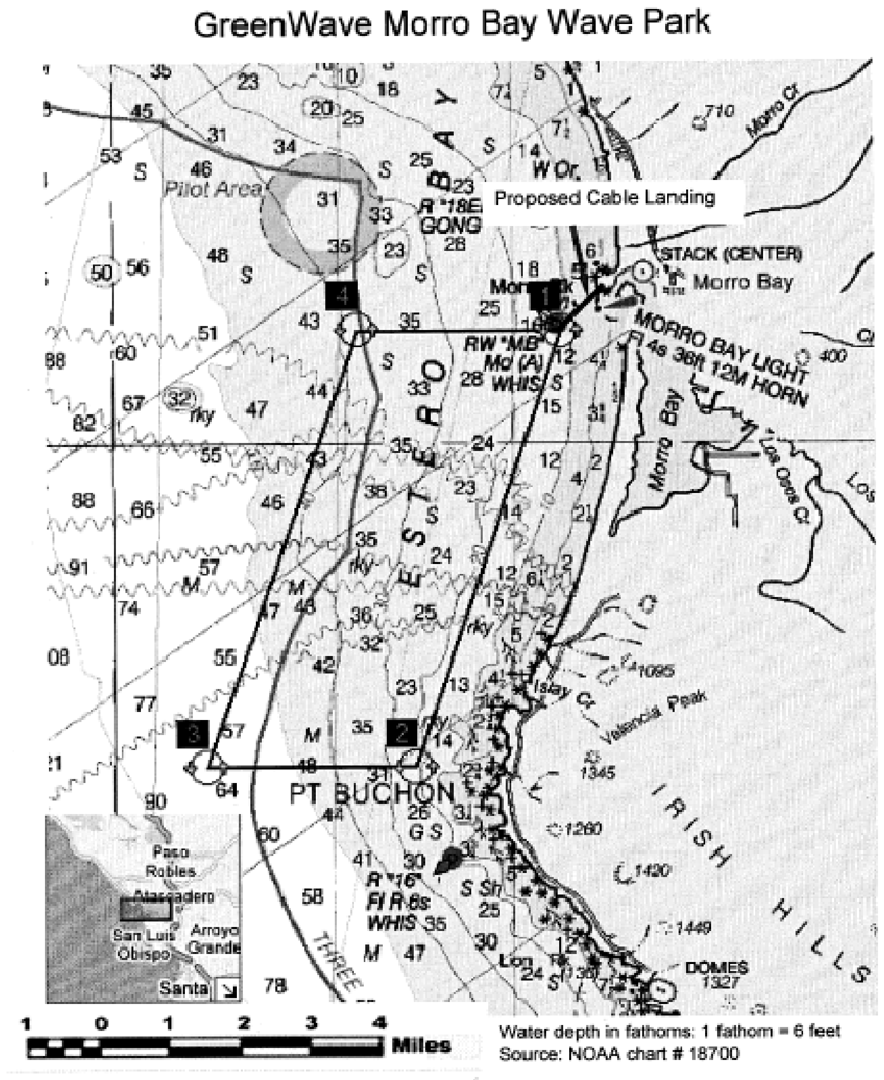


Figure 31. GreenWave San Luis Obispo Wave Park project map.

Permit status	Project capacity	Approximate size of project area	WEC manufacturer specified	Proposed date of construction
FERC preliminary permit application issued on 5/1/2009	Initial 5MW, Eventual 100MW	17 square miles	Not yet identified	2012

Table 10. GreenWave San Luis Obispo Wave Park project details.

APPENDIX B: WEC Manufacturer Requests for Information

The following RFI was adapted and sent to the following WEC Manufacturers:

Aquamarine Power
Green Ocean
AWS Ocean Energy
Renewable Energy Holdings
Cean Energy Ltd.
Pelamis Wave Power
Ocean Power Technologies
Finavera Renewables
Oceanlinx
Wavebob Ltd.
Power Buoy Technologies
Wave Gen

Example RFI, Finavera Renewables:

Finavera Renewables,

The California Polytechnic State University, San Luis Obispo (CPSUSLO), will be performing wave energy conversion site assessments for several sites on the Central California coast as part of a graduate thesis research project. The study aims to evaluate emerging commercial wave energy convertors (WECs) to determine the complete “wave to wire” cost of electricity (COE) for a theoretical 25MW capacity power WEC plant. General Engineering Graduate Student Dmitri Jarocki will be performing the analysis under the direction of Dr. Robert Crockett and Dr. James H. Wilson.

The analysis will be performed by matching performance specifications of several established WEC manufacturers with wave energy resource modeling per methods used by J. H. Wilson and A. Beyene in the California Wave Energy Resource Evaluation (2007). Annual WEC output estimations will follow methods used by K. Nielsen in Subtask II.2 of the International Energy Agency Implementation Agreement for a Cooperative Program on Ocean Energy Systems (2002). Economic analysis will include all costs for a 25-year lifecycle of a 25MW plant, and will aim to determine the minimum COE at each location.

Locations include several sites being actively pursued by developers for federal and state permitting, and findings may be influential in WEC selection for future full scale commercial ventures. Performance specifications for several prominent WEC manufactures including Pelamis and Oceanlinx have already been obtained, and without performance specifications, the AquaBuoy cannot be considered for comparison as an emerging commercial WEC. Due to the proprietary nature of WEC performance, CPSUSLO and all investigators will voluntarily agree to sign a non disclosure agreement (NDA) with you to ensure the specifications are not published or disclosed.

Information required for inclusion in the study is chiefly the expected power output of the AquaBuoy as a function of significant wave height and wave period. Provided performance information would preferably be in the format of Capture Width Ratios (CWR) for the significant wave heights and peak periods contained in the attached table. Methods for CWR calculation can be found in the E21 Electric Powers Research Institute (EPRI) Specification[1], which can be supplied if desired. If CWR data is unavailable, a power curve plot of power absorbed as a function of significant wave height would be sufficient. Additionally, estimated device cost and mooring configuration parameters will be needed for a 25 MW plant capacity.

Requests for information have been extended to the following WEC manufactures: Pelamis Wave Power, Finavera Renewables, Wave Dragon, Renewable Energy Holdings, Wavebob, Ocean Power Technologies, Aquamarine Power, AWS Ocean Energy, Bio Power, Green Ocean, Ocean Energy Ltd., and Oceanlinx.

As research is being conducted, respect and protection of proprietary information will remain paramount. Specific performance specifications shall be excluded from any published materials if required, and if necessary, further intellectual property protection options can be thoroughly discussed.

Thank you for your consideration and cooperation,

Dmitri Jarocki

Graduate Student
Department of General Engineering
California Polytechnic University, San Luis Obispo
djarocki@calpoly.edu
ph. (805) 234-7657

AquaBuoy CAPTURE WIDTH RATIO (CWR)									
Hs (m)	**Tp (seconds)**								
	7	**8**	**9**	**10**	**11**	**12**	**14**	**15**	**17**
5									
4.5									
4									
3.5									
3									
2.5									
2									
1.5									
1									

CWR = P_{abs} / (J x D_y)

Where :

CWR is the capture width ratio (dimensionless)

P_{abs} is the absorbed power in simulated or modeled seastate (kW)

Tp is the peak period (seconds)

J is the incident power in simulated or modeled seastate (kW/m)

D_y is the cross-wave dimension of the simulated device or test model (meters) which would be the diameter of a buoy or beam of a rectangular raft

[1] For further explanation of the CWR, please see E21 EPRI Specification for Guidelines for Preliminary Estimation of Power Production by Offshore Wave Energy Conversion Devices (2003), E21 EPRI – WP – US – 001 (attached).

APPENDIX C: Swan Plots

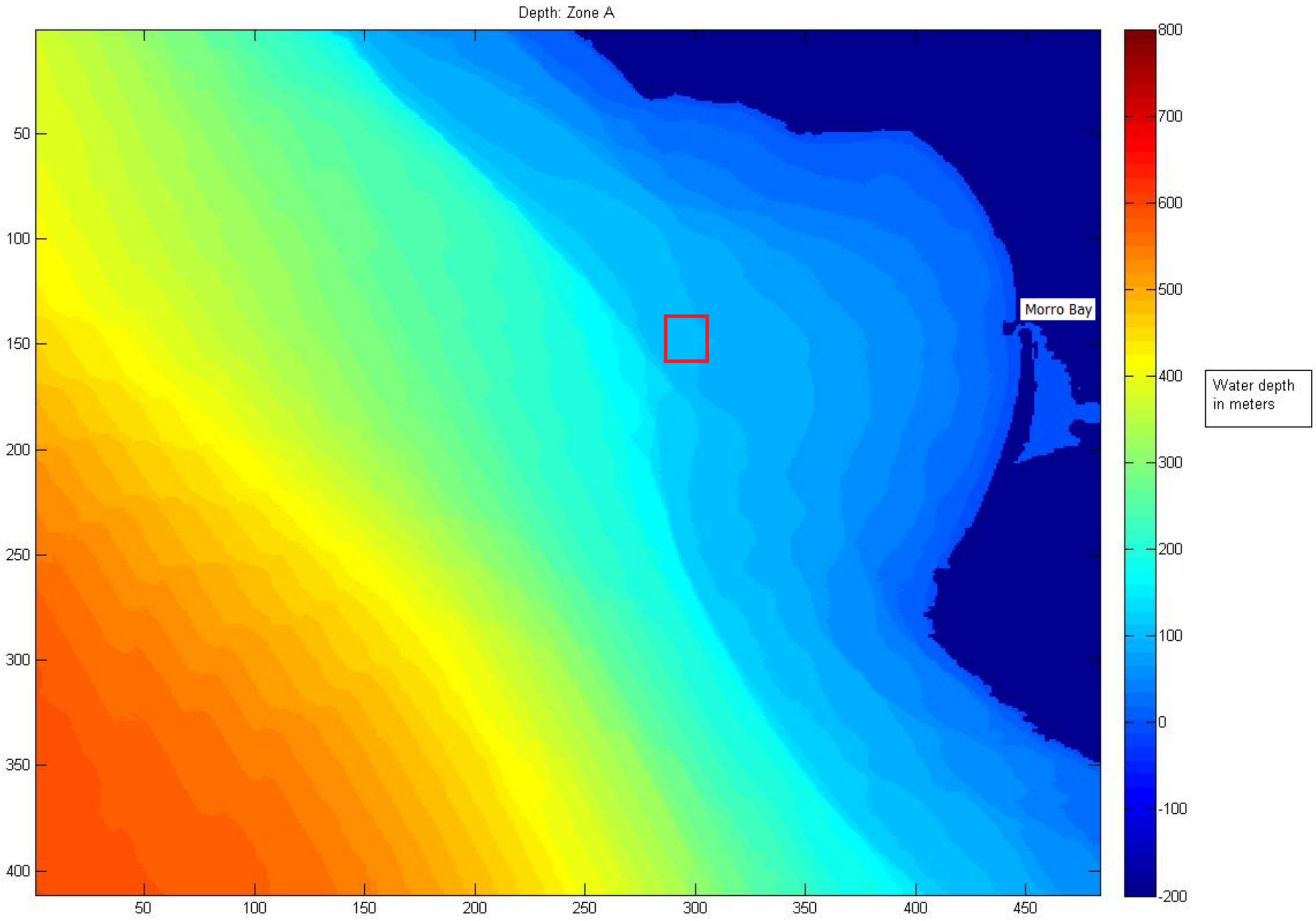


Figure 32. Plotted bottom data input for SWAN modeling at Site A.

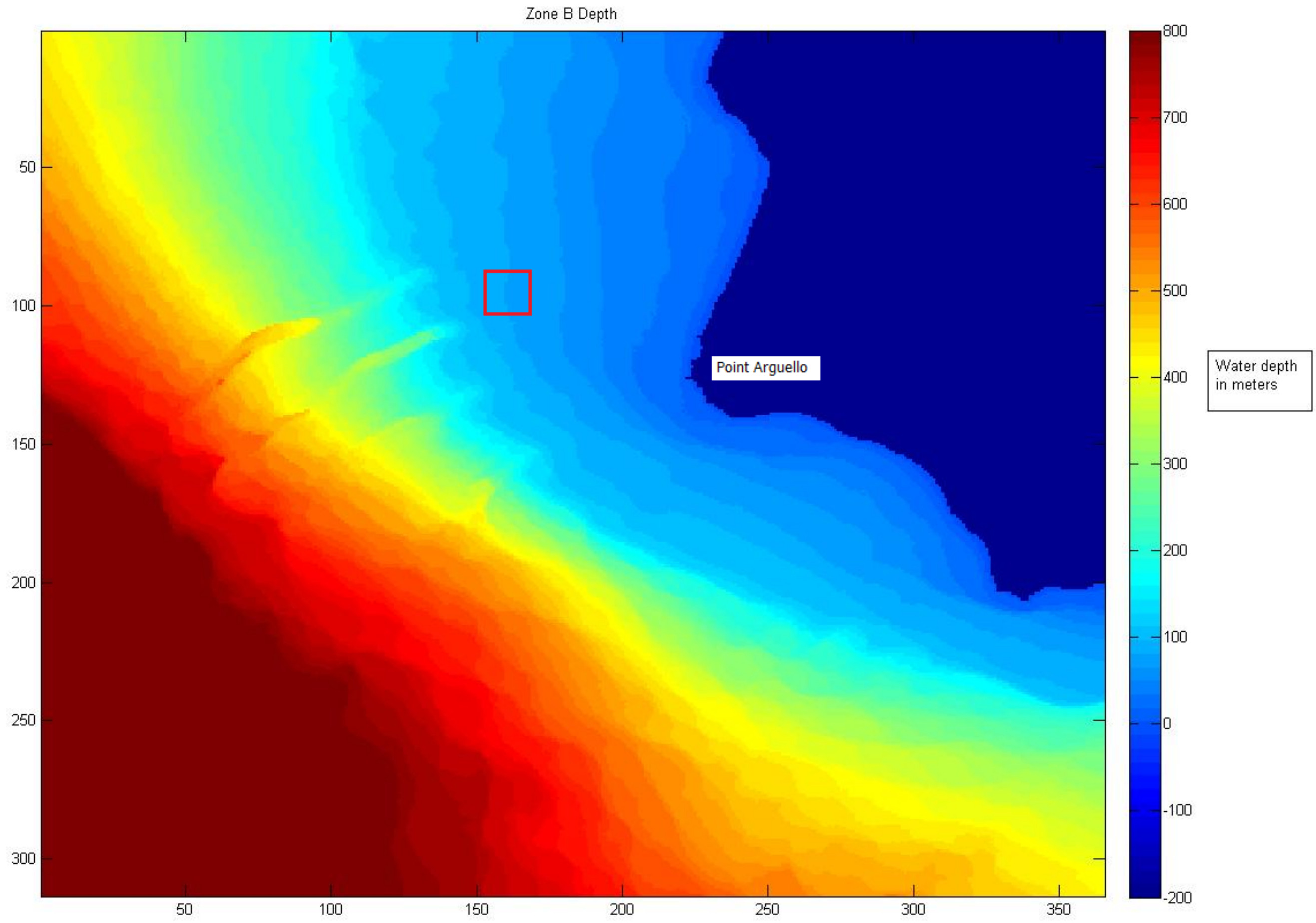


Figure 33. Plotted bottom data input for SWAN modeling at Site B.

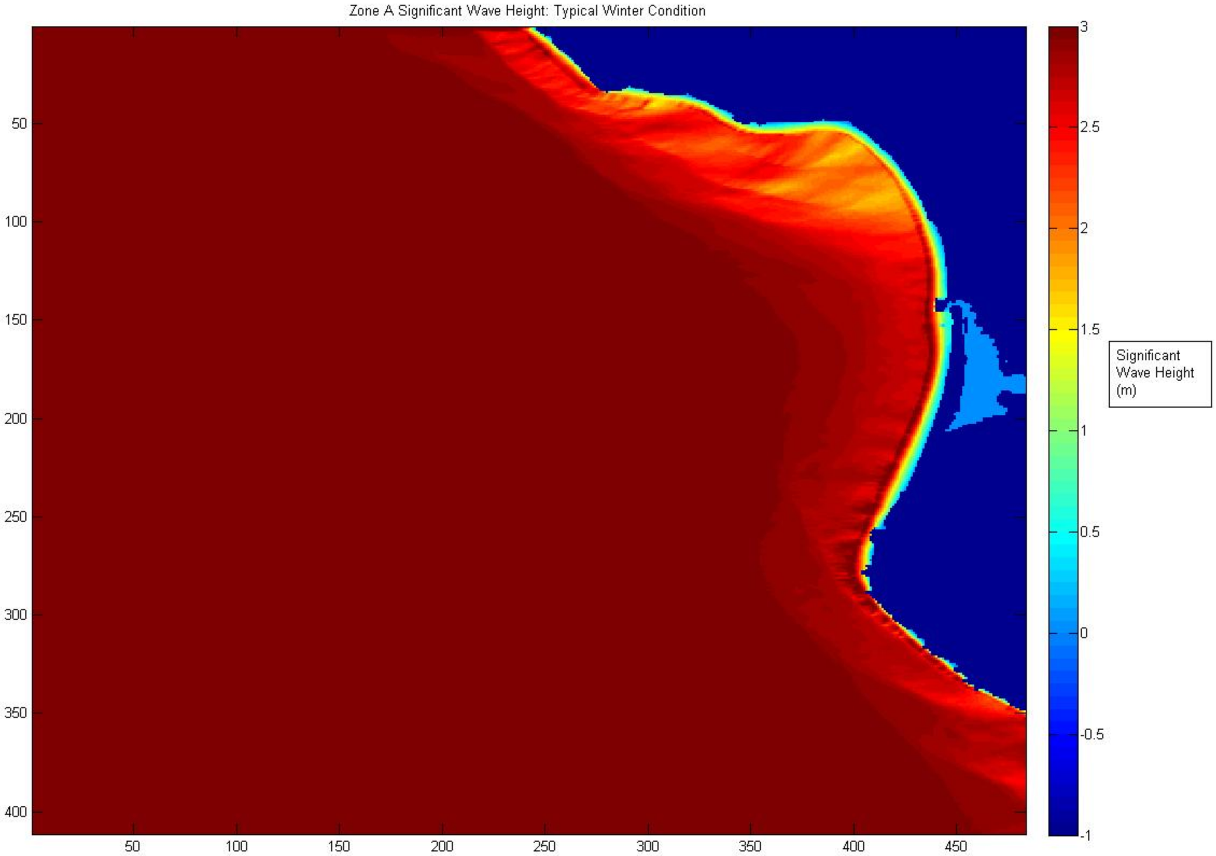


Figure 34. Significant wave height during typical winter swell, Site A.

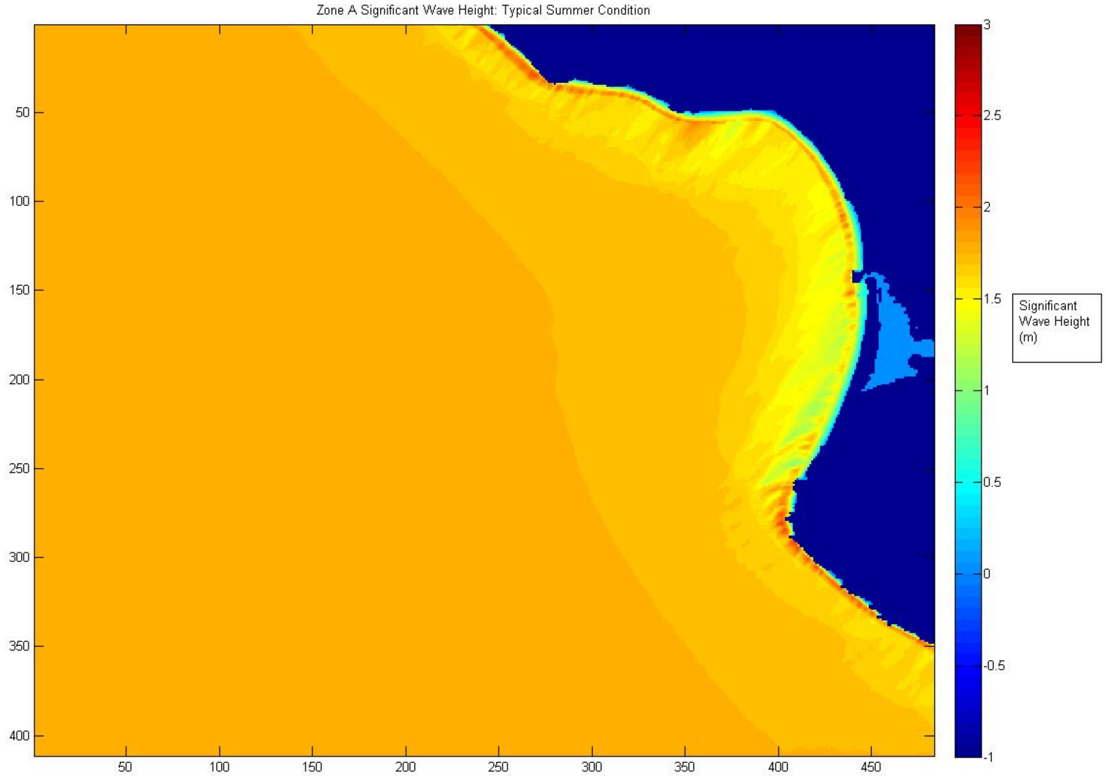


Figure 35. Significant wave height during typical summer swell, Site A.

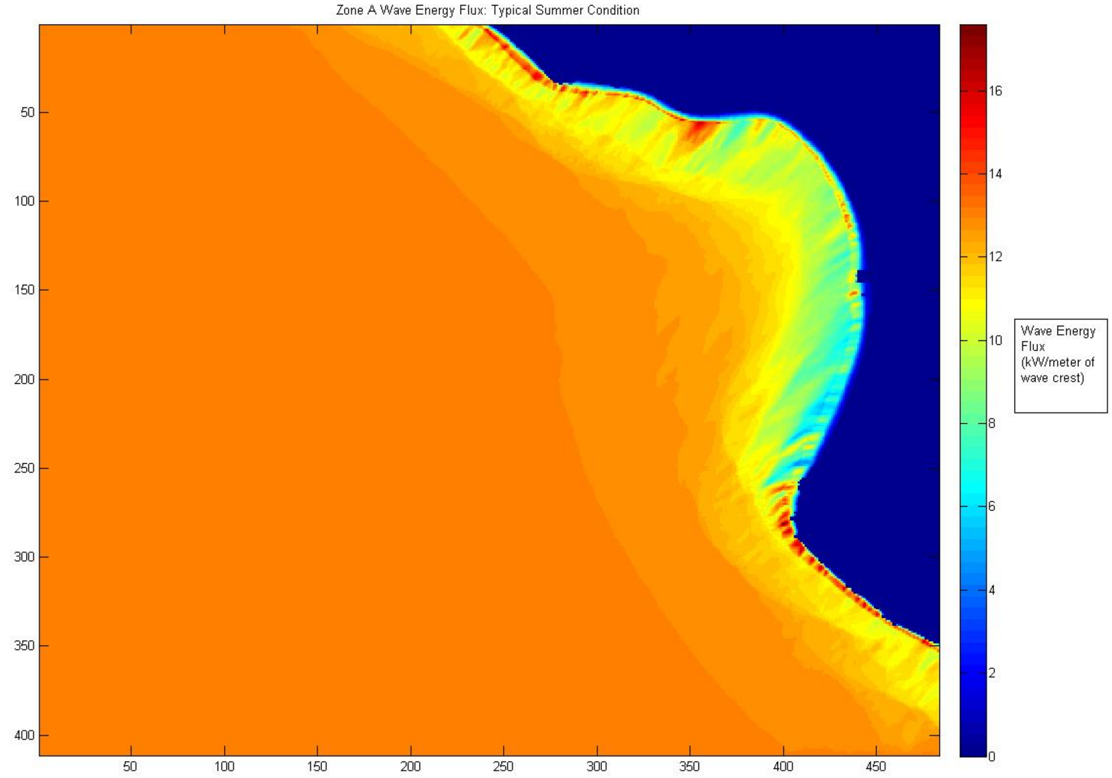


Figure 36. Wave energy flux during typical summer swell conditions at Site A.

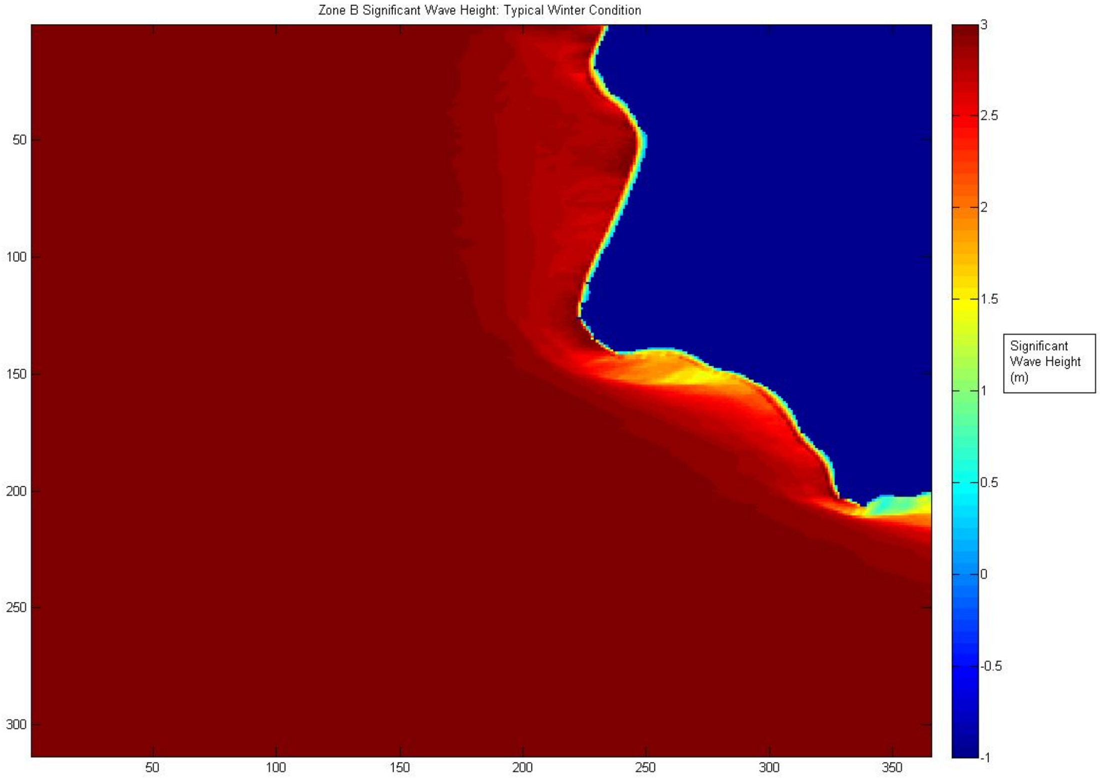


Figure 37. Significant wave height during typical winter swell, Site B.

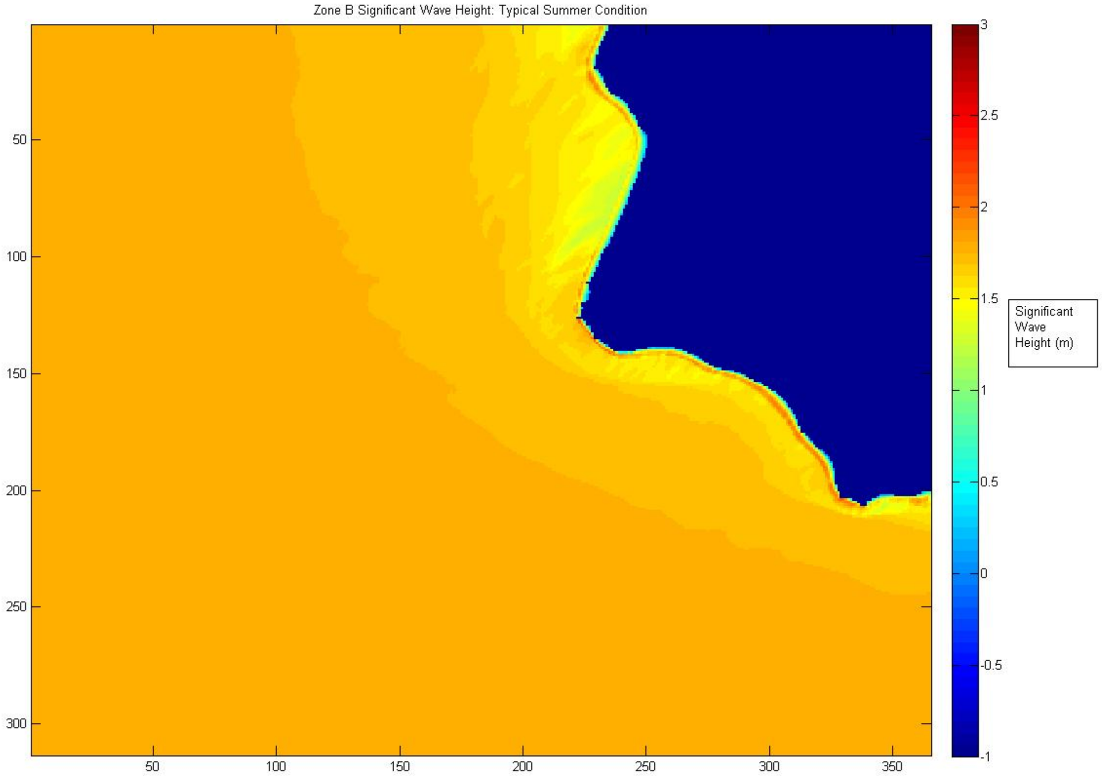


Figure 38. Wave energy flux during typical summer swell conditions, Site B.

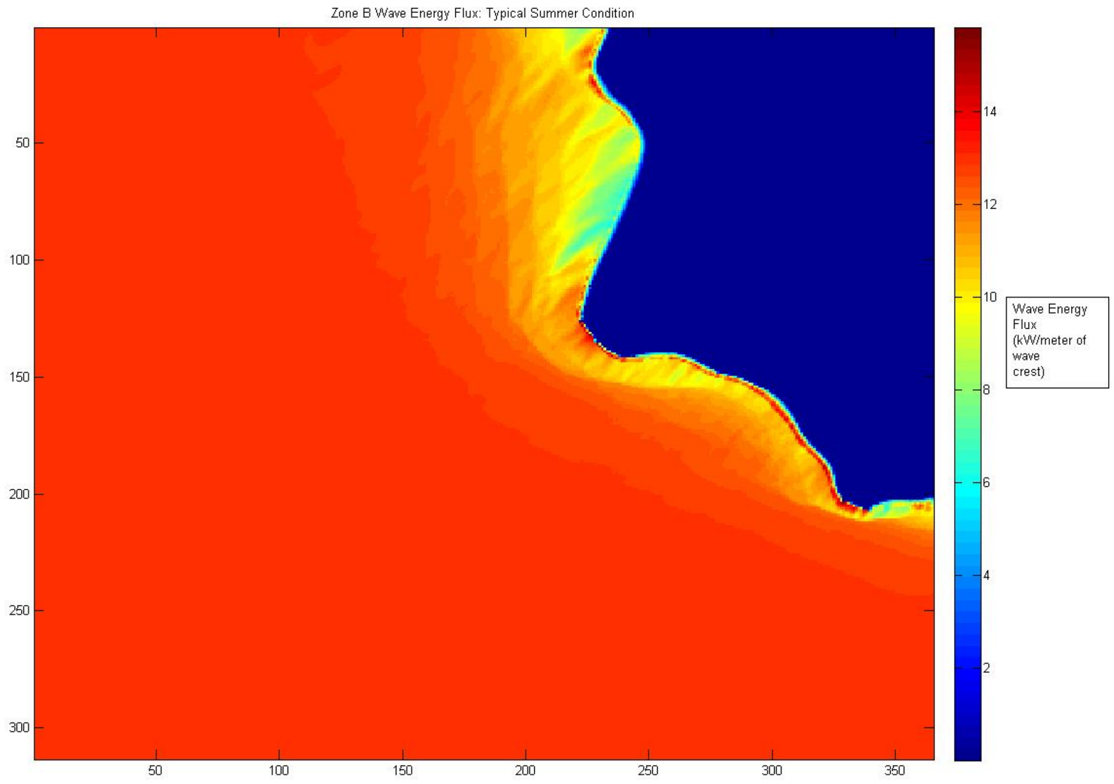
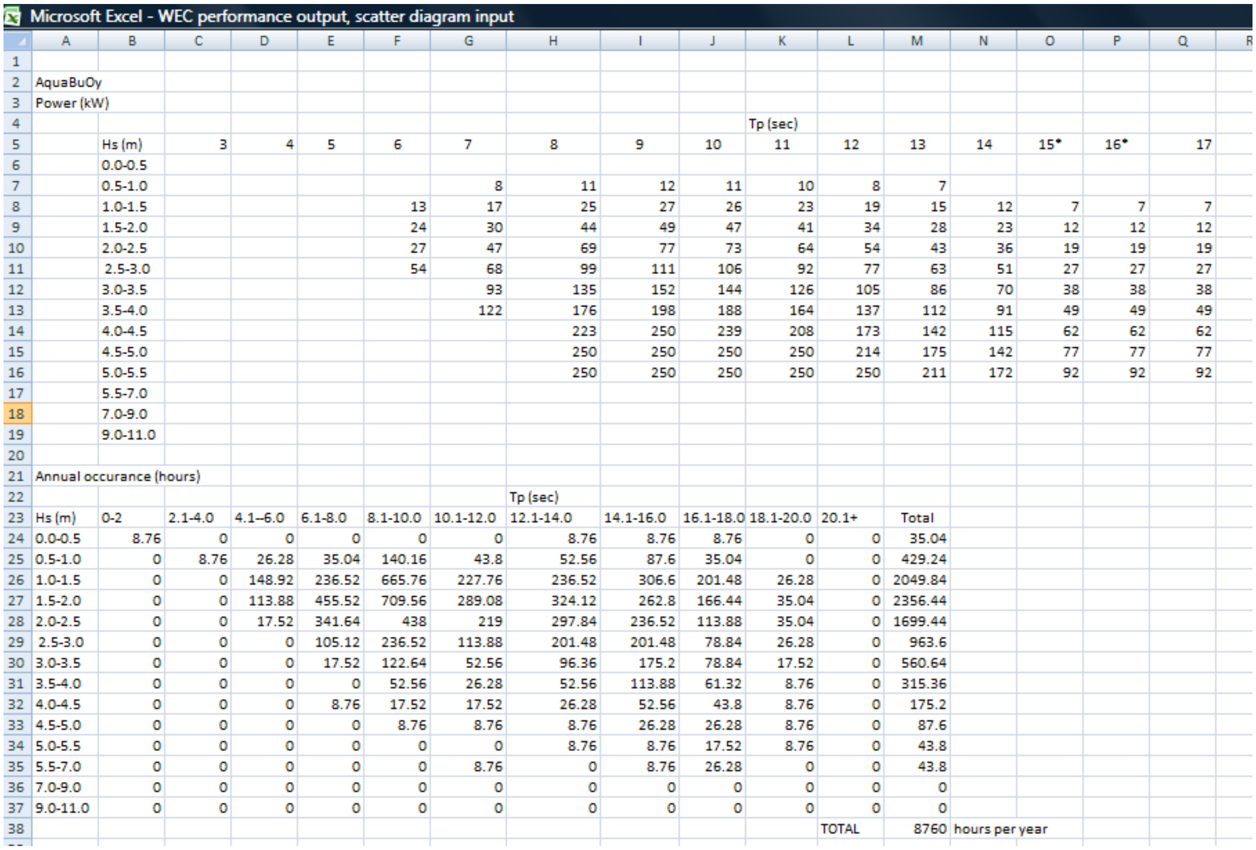


Figure 39. Wave energy flux during typical summer swell conditions, Site B.

APPENDIX D: WEC Performance Specifications and Power Production Spreadsheets



Microsoft Excel - WEC performance output, scatter diagram input

AquaBuOy

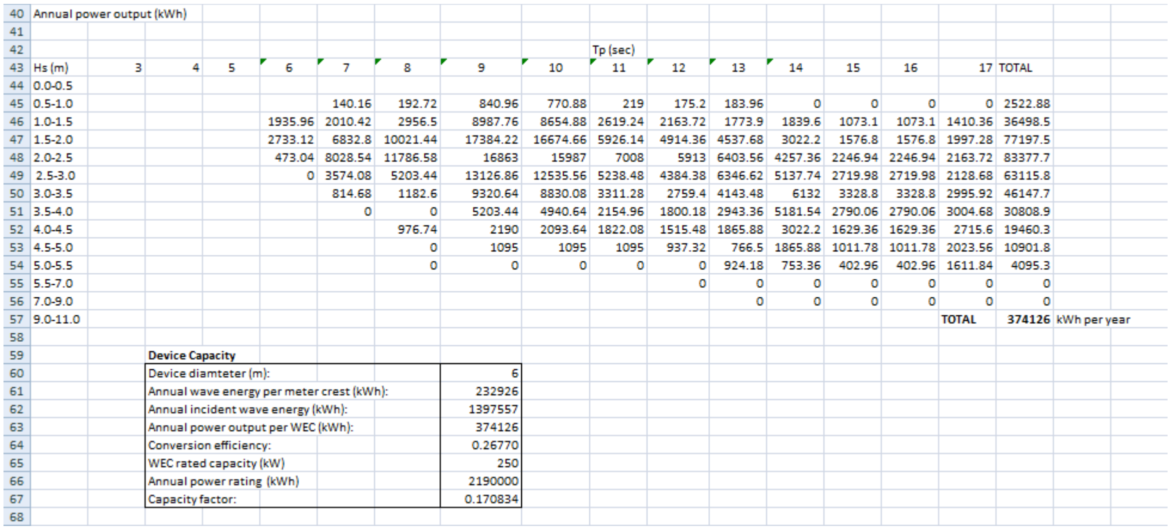
Power (kW)

	Tp (sec)														
Hs (m)	3	4	5	6	7	8	9	10	11	12	13	14	15*	16*	17
0.0-0.5															
0.5-1.0					8	11	12	11	10	8	7				
1.0-1.5				13	17	25	27	26	23	19	15	12	7	7	7
1.5-2.0				24	30	44	49	47	41	34	28	23	12	12	12
2.0-2.5				27	47	69	77	73	64	54	43	36	19	19	19
2.5-3.0				54	68	99	111	106	92	77	63	51	27	27	27
3.0-3.5					93	135	152	144	126	105	86	70	38	38	38
3.5-4.0					122	176	198	188	164	137	112	91	49	49	49
4.0-4.5						223	250	239	208	173	142	115	62	62	62
4.5-5.0						250	250	250	250	214	175	142	77	77	77
5.0-5.5						250	250	250	250	250	211	172	92	92	92
5.5-7.0															
7.0-9.0															
9.0-11.0															

Annual occurance (hours)

							Tp (sec)					
Hs (m)	0-2	2.1-4.0	4.1--6.0	6.1-8.0	8.1-10.0	10.1-12.0	12.1-14.0	14.1-16.0	16.1-18.0	18.1-20.0	20.1+	Total
0.0-0.5	8.76	0	0	0	0	0	8.76	8.76	8.76	0	0	35.04
0.5-1.0	0	8.76	26.28	35.04	140.16	43.8	52.56	87.6	35.04	0	0	429.24
1.0-1.5	0	0	148.92	236.52	665.76	227.76	236.52	306.6	201.48	26.28	0	2049.84
1.5-2.0	0	0	113.88	455.52	709.56	289.08	324.12	262.8	166.44	35.04	0	2356.44
2.0-2.5	0	0	17.52	341.64	438	219	297.84	236.52	113.88	35.04	0	1699.44
2.5-3.0	0	0	0	105.12	236.52	113.88	201.48	201.48	78.84	26.28	0	963.6
3.0-3.5	0	0	0	17.52	122.64	52.56	96.36	175.2	78.84	17.52	0	560.64
3.5-4.0	0	0	0	0	52.56	26.28	52.56	113.88	61.32	8.76	0	315.36
4.0-4.5	0	0	0	8.76	17.52	17.52	26.28	52.56	43.8	8.76	0	175.2
4.5-5.0	0	0	0	0	8.76	8.76	8.76	26.28	26.28	8.76	0	87.6
5.0-5.5	0	0	0	0	0	0	8.76	8.76	17.52	8.76	0	43.8
5.5-7.0	0	0	0	0	0	8.76	0	8.76	26.28	0	0	43.8
7.0-9.0	0	0	0	0	0	0	0	0	0	0	0	0
9.0-11.0	0	0	0	0	0	0	0	0	0	0	0	0
											TOTAL	8760 hours per year

Figure 40. Excel spreadsheet of AquaBuOY performance specification and wave statistic scatter diagram.



Annual power output (kWh)

									Tp (sec)						
Hs (m)	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	TOTAL
0.0-0.5																
0.5-1.0					140.16	192.72	840.96	770.88	219	175.2	183.96	0	0	0	0	2522.88
1.0-1.5				1935.96	2010.42	2956.5	8987.76	8654.88	2619.24	2163.72	1773.9	1839.6	1073.1	1073.1	1410.36	36498.5
1.5-2.0				2733.12	6832.8	10021.44	17384.22	16674.66	5926.14	4914.36	4537.68	3022.2	1576.8	1576.8	1997.28	77197.5
2.0-2.5				473.04	8028.54	11786.58	16863	15987	7008	5913	6403.56	4257.36	2246.94	2246.94	2163.72	83377.7
2.5-3.0				0	3574.08	5203.44	13126.86	12535.56	5238.48	4384.38	6346.62	5137.74	2719.98	2719.98	2128.68	63115.8
3.0-3.5					814.68	1182.6	9320.64	8830.08	3311.28	2759.4	4143.48	6132	3328.8	3328.8	2995.92	46147.7
3.5-4.0					0	0	5203.44	4940.64	2154.96	1800.18	2943.36	5181.54	2790.06	2790.06	3004.68	30808.9
4.0-4.5						976.74	2190	2093.64	1822.08	1515.48	1865.88	3022.2	1629.36	1629.36	2715.6	19460.3
4.5-5.0						0	1095	1095	1095	937.32	766.5	1865.88	1011.78	1011.78	2023.56	10901.8
5.0-5.5						0	0	0	0	0	924.18	753.36	402.96	402.96	1611.84	4095.3
5.5-7.0										0	0	0	0	0	0	0
7.0-9.0											0	0	0	0	0	0
9.0-11.0															TOTAL	**374126** kWh per year

Device Capacity

Device diamteter (m):	6
Annual wave energy per meter crest (kWh):	232926
Annual incident wave energy (kWh):	1397557
Annual power output per WEC (kWh):	374126
Conversion efficiency:	0.26770
WEC rated capacity (kW)	250
Annual power rating (kWh)	2190000
Capacity factor:	0.170834

Figure 41. Excel spreadsheet of AquaBuOY power production calculations.

APPENDIX E: Economic Analysis Calculation Spreadsheets

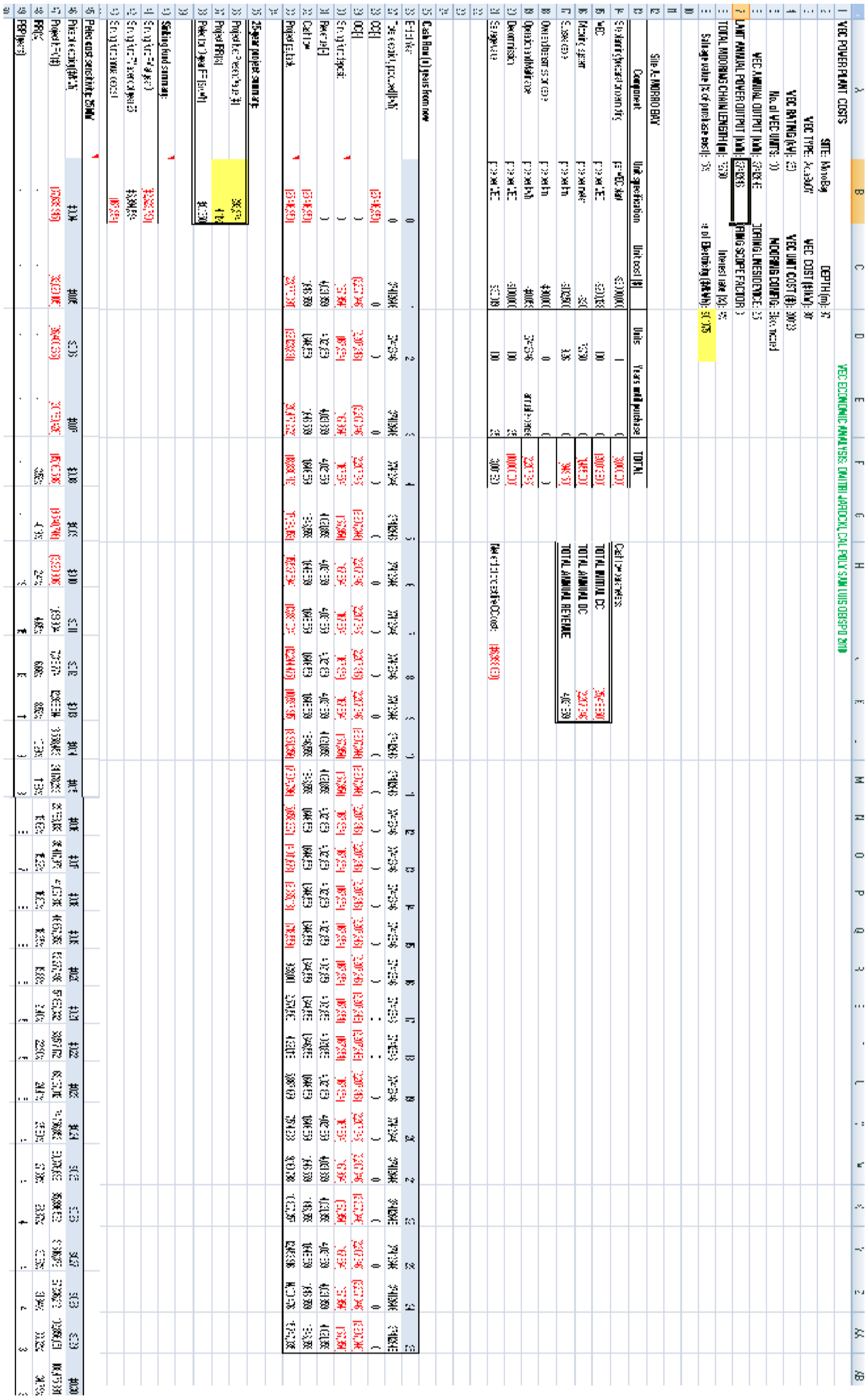


Figure 42. Excel spreadsheet containing AquaBuOY economic calculations.