Technology White Paper

on

Wave Energy Potential on the U.S. Outer Continental Shelf

Minerals Management Service
Renewable Energy and Alternate Use Program
U.S. Department of the Interior

May 2006

WAVE ENERGY POTENTIAL ON THE U.S. OUTER CONTINENTAL SHELF

INTRODUCTION

With the passage of the Energy Policy Act of 2005 (EPAct), Public Law 109-58 (H.R. 6), the Minerals Management Service (MMS), a bureau of the U.S. Department of the Interior, was given jurisdiction over Renewable Energy and Alternate Use Program projects, such as wind, wave, ocean current, solar energy, hydrogen generation, and projects that make alternative use of existing oil and natural gas platforms in Federal waters. A new program within MMS has been established to oversee these operations on the U.S. Outer Continental Shelf (OCS). MMS is developing rules to guide the application and permitting process for development of Renewable Energy and Alternate Use Program projects on the OCS. To apply the requirements of the National Environmental Policy Act (NEPA) in the establishment of national offshore alternate energy development policy and a national alternate-energy-related use program and rules, MMS plans to prepare a programmatic environmental impact statement (Programmatic EIS). The Programmatic EIS process will (1) provide for public input concerning the scope of national issues associated with offshore alternate-energy-related use activities; (2) identify, define, and assess generic environmental, sociocultural, and economic impacts associated with offshore alternate-energy-related use activities; (3) evaluate and establish effective mitigation measures and best management practices to avoid, minimize, or compensate for potential impacts; and (4) facilitate future preparation of site-specific NEPA documents—subsequent NEPA documents prepared for site-specific Renewable Energy and Alternate Use Program projects will tier off of the Programmatic EIS and Record of Decision. The Programmatic EIS will evaluate the issues associated with development, including all foreseeable potential monitoring, testing, commercial development, operations, and decommissioning activities in Federal waters on the OCS. Information defining the issues and current technology will be obtained primarily from Federal research organizations, MMS, industry, and other valid sources.

In preparation for the Programmatic EIS, MMS has developed a series of White Papers on topics of interest to the Renewable Energy and Alternate Use Program. The overall objective of the White Papers is to provide sufficient information on the prospective alternative technologies to support assessments of the potential environmental impacts of the technologies and of the viable impact mitigation strategies in the Programmatic EIS. The White Papers also will serve as sources of information for stakeholder outreach.

This paper discusses the generation of energy from ocean waves on the U.S. OCS. Resource potential and technologies for capturing the energy in the waves are discussed.[1] Major environmental and economic considerations that can be surmised from available literature at this time for the development of this energy resource are listed. Companion papers in the series address the generation of energy on the OCS from wind, solar radiation, and ocean currents, and

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[1] Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not represent its endorsement, recommendation, or favoring by MMS, the United States government, or any agency thereof.

the transportation of energy generated on the OCS to onshore as electricity or in the form of hydrogen.

RESOURCE POTENTIAL

Ocean waves represent a form of renewable energy created by wind currents passing over open water. Capturing the energy of ocean waves in offshore locations has been demonstrated as technically feasible. Also, basic research to develop improved designs of wave energy conversion (WEC) devices is being conducted in regions such as near the Oregon coast, which is a high wave energy resource (Rhinefrank 2005). Compared with other forms of offshore renewable energy, such as solar photovoltaic (PV), wind, or ocean current, wave energy is continuous but highly variable, although wave levels at a given location can be confidently predicted several days in advance.

The common measure of wave power, P, is

$P = \frac{\rho g^2 T H^2}{32\pi}$ watt per meter (W/m) of crest length (distance along an individual crest),

where:

ρ = the density of seawater = 1,025 kg/m^3,

g = acceleration due to gravity = 9.8 m/s/s,

T = period of wave (s), and

H = wave height (m).

Because wind is generated by uneven solar heating, wave energy can be considered a concentrated form of solar energy. Incoming solar radiation levels that are on the order of 100 W/m^2 are transferred into waves with power levels that can exceed 1,000 kW/m of wave crest length. The transfer of solar energy to waves is greatest in areas with the strongest wind currents (primarily between 30° and 60° latitude), near the equator with persistent trade winds, and in high altitudes because of polar storms.

Waves are also efficient transporters of solar energy. Storm winds generally create irregular and complex waves. In deep water, after the storm winds die down, the storm waves can travel thousands of kilometers in the form of regular smooth waves, or swells, that retain much of the energy of the original storm waves. The energy in swells or waves dissipates after it reaches waters that are less than ~200 m deep. At 20-m water depths, the wave’s energy typically drops to about one-third of the level it had in deep water.

The total annual average wave energy off the U.S. coastlines (including Alaska and Hawaii), calculated at a water depth of 60 m has been estimated (Bedard et al. 2005) at 2,100 Terawatt-hours (TWh) ($2{,}100 \times 10^{12}$ Wh).[2]

Estimates of the worldwide economically recoverable wave energy resource are in the range of 140 to 750 TWh/yr for existing wave-capturing technologies that have become fully mature (ETNWG 2003). With projected long-term technical improvements, this could be increased by a factor of 2 to 3 (Thorpe 1999). The fraction of the total wave power that is economically recoverable in U.S. offshore regions has not been estimated, but is significant even if only a small fraction of the 2,100 TWh/yr available is captured. (Currently, approximately 11,200 TWh/yr of primary energy is required to meet total U.S. electrical demand.) WEC devices have the greatest potential for applications at islands such as Hawaii because of the combination of the relatively high ratio of available shoreline per unit energy requirement, availability of greater unit wave energies due to trade winds, and the relatively high costs of other local energy sources.

RESOURCE UTILIZATION TECHNOLOGIES

A variety of technologies have been proposed to capture the energy from waves; however, each is in too early a stage of development to predict which technology or mix of technologies would be most prevalent in future commercialization. Some of the technologies that have been the target of recent developmental efforts and are appropriate for the offshore applications being considered in this assessment are terminators, attenuators, point absorbers, and overtopping devices.

Terminators

Terminator devices extend perpendicular to the direction of wave travel and capture or reflect the power of the wave. These devices are typically installed onshore or nearshore; however, floating versions have been designed for offshore applications. The oscillating water column (OWC) is a form of terminator in which water enters through a subsurface opening into a chamber with air trapped above it. The wave action causes the captured water column to move up and down like a piston to force the air though an opening connected to a turbine. A full-scale, 500-kW, prototype OWC designed and built by Energetech (2006) (Figure 1) is undergoing testing offshore at Port Kembla in Australia, and a further project is under development for Rhode Island.

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[2] This estimate was made at a specified water depth of 60 m (irrespective of the distance from the shore at which that depth occurs) in order to allow comparisons of wave energies between coastal areas and to eliminate the possible, but unpredictable loss of energy of the wave through its interactions with the sea bottom (scouring) at shallower depths. Typical wave energy in U.S. offshore regions ranges from 2 to 6 kW/m in the mid-Atlantic, 12 to 22 kW/m in regions such as Hawaii with trade winds, and 36 to 72 kW/m in northwestern U.S. coastal areas near Washington and Oregon.

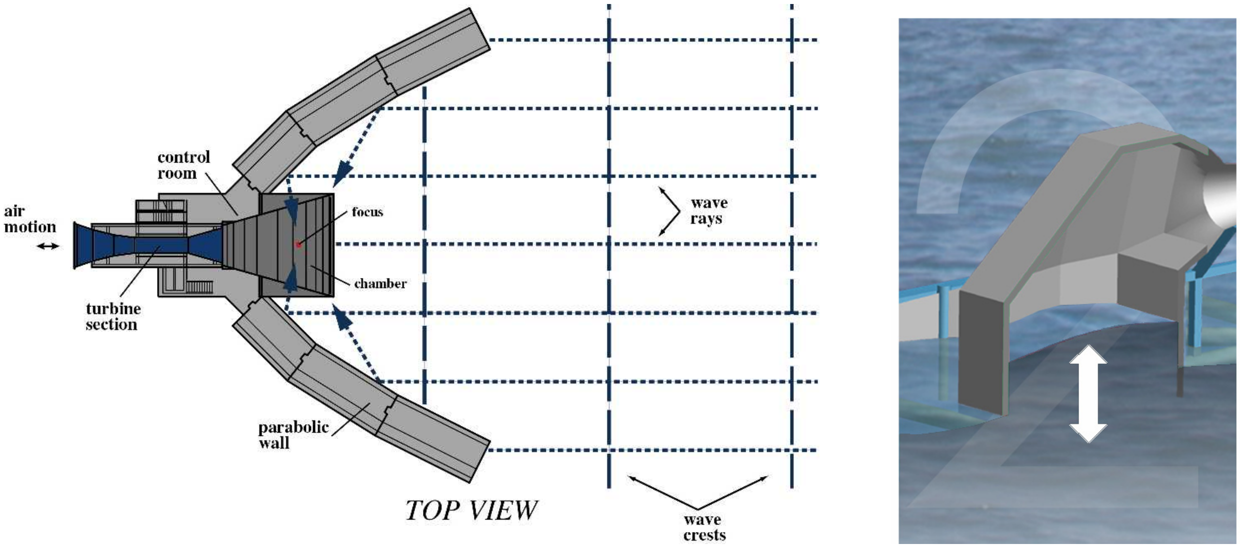

FIGURE 1 Oscillating Water Column (Source: Energetech 2006)

In an Electric Power Research Institute (EPRI)-cosponsored study (Bedard et al. 2005), a design, performance, and cost assessment was conducted for an Energetech commercial-scale OWC with a 1,000-kW rated capacity, sited 22 km from the California shore. With the wave conditions at this site (20 kW/m average annual), the estimated annual energy produced was 1,973 MWh/yr. For a scaled-up commercial system with multiple units producing 300,000 MWh/yr, the estimated cost of electricity would be on the order of $0.10/kWh.

Another floating OWC is the “Mighty Whale” offshore floating prototype, which has been under development at the Japan Marine Science and Technology Center since 1987 (JAMSTC 2006)

Attenuators

Attenuators are long multisegment floating structures oriented parallel to the direction of the wave travel. The differing heights of waves along the length of the device causes flexing where the segments connect, and this flexing is connected to hydraulic pumps or other converters. The attenuators with the most advanced development are the McCabe wave pump and the Pelamis by Ocean Power Delivery, Ltd. (2006).

The McCabe wave pump (Figure 2) has three pontoons linearly hinged together and pointed parallel to the wave direction. The center pontoon is attached to a submerged damper plate, which causes it to remain still relative to fore and aft pontoons. Hydraulic pumps attached between the center and end pontoons are activated as the waves force the end pontoons up and down. The pressurized hydraulic fluid can be used to drive a motor generator or to pressurize water for desalinization. A full-size 40-m prototype was tested off the coast of Ireland in 1996, and commercial devices are being offered by the manufacturer.

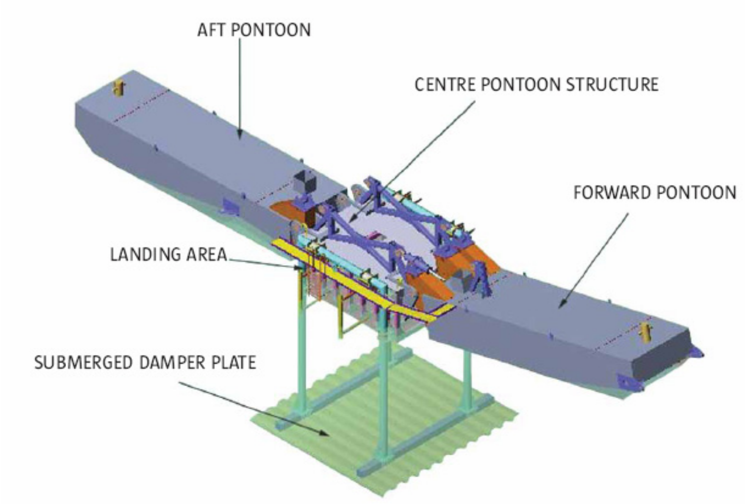

FIGURE 2 McCabe Wave Pump (Source: Polaski 2003)

A similar concept is used by the Pelamis (designed by Ocean Power Delivery Ltd. [2006]), which has four 30-m long by 3.5-m diameter floating cylindrical pontoons connected by three hinged joints (Figure 3). Flexing at the hinged joints due to wave action drives hydraulic pumps built into the joints. A full-scale, four-segment production prototype rated at 750 kW was sea tested for 1,000 hours in 2004. This successful demonstration was followed by the first order in 2005 of a commercial WEC system from a consortium led by the Portuguese power company Enersis SA. The first stage, scheduled to be completed in 2006, consists of three Pelamis machines with a combined rating of 2.25 MW to be sited about 5 km off the coast of northern Portugal. An expansion to more than 20-MW capacity is being considered. A Pelamis-powered 22.5-W wave energy facility is also planned for Scotland, with the first phase targeted for 2006.

The EPRI wave energy feasibility demonstration project has selected the Pelamis as one of the technologies for design, performance, cost, and economic assessment (Bedard et al. 2005). Sites for evaluation were selected off the coasts of Hawaii (15.2 kW/m average annual wave energy), Oregon (21.2 kW/m), California (11.2 kW/m), Massachusetts (13.8 kW/m), and Maine (4.9 kW/m). For systems at these sites scaled to a commercial level generating 300,000 MWh/yr, the cost of electricity ranged from about \$0.10/kWh for the areas with high wave energy, to about \$0.40/kWh for Maine, which has relatively lower levels of wave energy.

Point Absorbers

Point absorbers have a small horizontal dimension compared with the vertical dimension and utilize the rise and fall of the wave height at a single point for WEC.

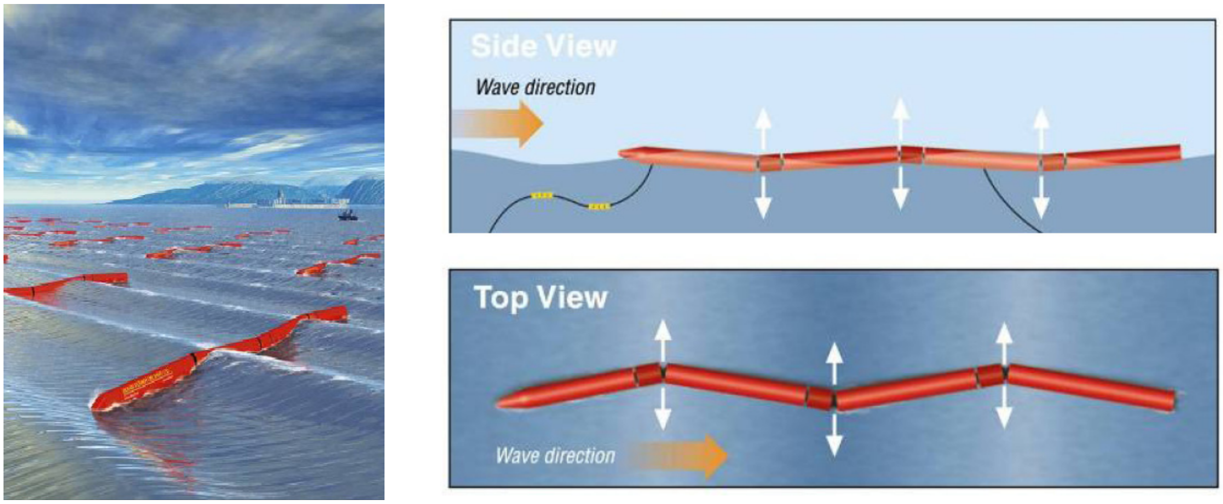

FIGURE 3 Pelamis Wave Energy Converter (Source: Ocean Power Delivery Ltd. 2006)

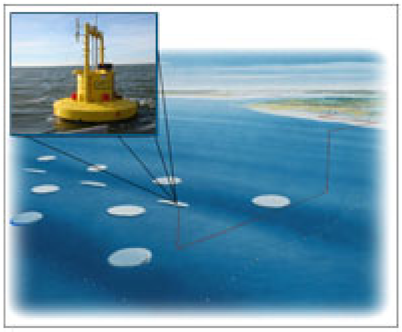

FIGURE 4 PowerBuoy Point Absorber Wave Energy Converter (Source: Ocean Power Technologies 2006)

One such device is the PowerBuoy™ developed by Ocean Power Technologies (2006) (Figure 4). The construction involves a floating structure with one component relatively immobile, and a second component with movement driven by wave motion (a floating buoy inside a fixed cylinder). The relative motion is used to drive electromechanical or hydraulic energy converters. A PowerBuoy demonstration unit rated at 40 kW was installed in 2005 for testing offshore from Atlantic City, New Jersey. Testing in the Pacific Ocean is also being conducted, with a unit installed in 2004 and 2005 off the coast of the Marine Corps Base in Oahu, Hawaii. A commercial-scale PowerBuoy system is planned for the northern coast of Spain, with an initial wave park (multiple units) at a 1.25-MW rating. Initial operation is expected in 2007.

The AquaBuOY™ WEC (Figure 5) being developed by the AquaEnergy Group, Ltd. (2005) is a point absorber that is the third generation of two Swedish designs that utilize the wave energy to pressurize a fluid that is then used to drive a turbine generator. The vertical movement of the buoy drives a broad, neutrally buoyant disk acting as a water piston contained in a long tube beneath the buoy. The water piston motion in turn elongates and relaxes a hose containing seawater, and the change in hose volume acts as a pump to pressurize the seawater. The AquaBuOY design has been tested using a full-scale prototype, and a 1-MW pilot offshore demonstration power plant is being developed offshore at Makah Bay, Washington. The Makah Bay demonstration will include four units rated at 250 kW placed 5.9 km (3.2 nautical miles) offshore in water approximately 46 m deep.

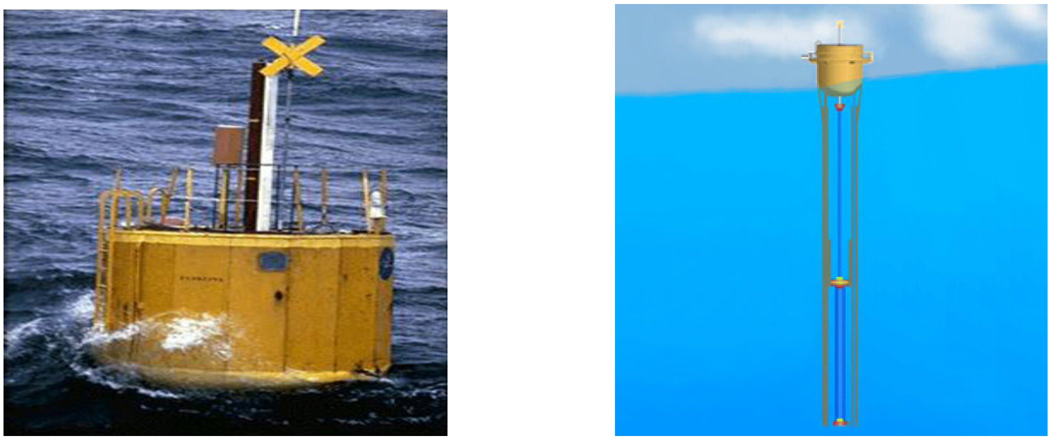

FIGURE 5 AquaBuOY Point Absorber Wave Energy Converter (Source: AquaEnergy Group, Ltd. 2005)

Other point absorbers that have been tested at prototype scale include the Archimedes Wave Swing (2006), which consists of an air-filled cylinder that moves up and down as waves pass over. This motion relative to a second cylinder fixed to the ocean floor is used to drive a linear electrical generator. A 2-MW capacity device has been tested offshore of Portugal.

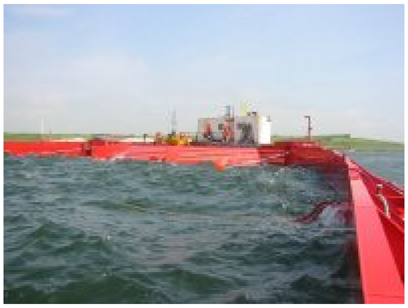

FIGURE 6 Wave Dragon Overtopping Device (Source: Wave Dragon 2005)

Overtopping Devices

Overtopping devices have reservoirs that are filled by impinging waves to levels above the average surrounding ocean. The released reservoir water is used to drive hydro turbines or other conversion devices. Overtopping devices have been designed and tested for both onshore and floating offshore applications. The offshore devices include the Wave Dragon™ (Wave Dragon 2005), whose design includes wave reflectors that concentrate the waves toward it and thus raises the effective wave height. Wave Dragon development includes a 7-MW demonstration project off the coast of Wales and a precommercial prototype project performing long-term and real sea tests on hydraulic behavior, turbine strategy, and power production to the grid in Denmark. The Wave Dragon design has been scaled to 11 MW (Christensen 2006), but larger systems are feasible since the overtopping devices do not need to be in resonance with the waves as is the case for point absorbing devices.

The WavePlane™ (WavePlane Production 2006) overtopping device has a smaller reservoir. The waves are fed directly into a chamber that funnels the water to a turbine or other conversion device.

ENVIRONMENTAL CONSIDERATIONS

Conversion of wave energy to electrical or other usable forms of energy is generally anticipated to have limited environmental impacts. However, as with any emerging technology, the nature and extent of environmental considerations remain uncertain. The impacts that would potentially occur are also very site specific, depending on physical and ecological factors that vary considerably for potential ocean sites. As large-scale prototypes and commercial facilities are developed, these factors can be expected to be more precisely defined.

The following environmental considerations require monitoring.

Visual appearance and noise are device-specific, with considerable variability in visible freeboard height and noise generation above and below the water surface. Devices with OWCs and overtopping devices typically have the highest freeboard and are most visible. Offshore devices would require navigation hazard warning devices such as lights, sound signals, radar reflectors, and contrasting day marker painting. However, Coast Guard requirements only require that day markers be visible for 1 nautical mile (1.8 km), and thus offshore device markings would only be seen from shore on exceptionally clear days. The air being drawn in and expelled in OWC devices is likely to be the largest source of above-water noise. Some underwater noise would occur from devices with turbines, hydraulic pumps, and other moving parts. The frequency of the noise may also be a consideration in evaluating noise impacts.

Reduction in wave height from wave energy converters could be a consideration in some settings; however, the impact on wave characteristics would generally only be observed 1 to 2 km away from the WEC device in the direction of the wave travel. Thus there should not be a significant onshore impact if the devices were much more than this distance from the shore. None of the devices currently being developed would harvest a large portion of the wave energy, which would leave a relatively calm surface behind the devices. It is estimated that with current projections, a large wave energy facility with a maximum density of devices would cause the reduction in waves to be on the order of 10 to 15%, and this impact would rapidly dissipate within a few kilometers, but leave a slight lessening of waves in the overall vicinity. Little information is available on the impact on sediment transport or on biological communities from a reduction in wave height offshore. An isolated impact, such as reduced wave height for recreational surfers, could possibly result.

Marine habitat could be impacted positively or negatively depending on the nature of additional submerged surfaces, above-water platforms, and changes in the seafloor. Artificial above-water surfaces could provide habitat for seals and sea lions or nesting areas for birds. Underwater surfaces of WEC devices would provide substrates for various biological systems, which could be a positive or negative complement to existing natural habitats. With some WEC devices, it may be necessary to control the growth of marine organisms on some surfaces.

Toxic releases may be of concern related to leaks or accidental spills of liquids used in systems with working hydraulic fluids. Any impacts could be minimized through the selection of nontoxic fluids and careful monitoring, with adequate spill response plans and secondary containment design features. Use of biocides to control growth of marine organisms may also be a source of toxic releases.

Conflict with other sea space users, such as commercial shipping and fishing and recreational boating, can occur without the careful selection of sites for WEC devices. The impact can potentially be positive for recreational and commercial fisheries if the devices provide for additional biological habitats.

Installation and decommissioning. Disturbances from securing the devices to the ocean floor and installation of cables may have negative impacts on marine habitats. Potential decommissioning impacts are primarily related to disturbing marine habitats that have adapted to the presence of the wave energy structures.

A detailed site-specific environmental assessment has been conducted for a project to install and test multiple WEC devices at the Marine Corps Base Hawaii, Kaneohe Bay (Department of the Navy 2003). A summary of this assessment is provided for illustrative reasons. The project involves installation and testing of up to six WEC devices of the point absorbers design. The WEC buoys are to be located in about 30 m of water approximately 1,200 m offshore, at two possible sites in Hawaii. The electrical power generated would be transmitted to shore via an underwater cable. Submerged equipment would be weighted and secured to the seafloor with rock bolts. The 10 potentially affected resources that were identified for this project are shoreline physiography, oceanographic conditions, marine biological resources, terrestrial biological resources, land and marine resource use compatibility, cultural resources, infrastructure, recreation, public safety, and visual resources. None of these resources were found to be significantly impacted by the proposed installation and operational testing. Installation procedures would be designed to minimize impacts on living coral and benthic communities by avoiding areas of rich biological diversity and high coral coverage. Growth of benthic organisms, such as corals and sponges, on the new substrate provided by the undersea components of the system may end up benefiting the ecosystem. Organisms sensitive to electric or magnetic fields may be able to detect stray currents or corona effects when very close to the undersea cable; however, the effects would be minor and temporary. It was determined that there would be no significant impacts on recreation and public safety, although recreational activities in the immediate vicinity of the buoy array would be somewhat curtailed for safety reasons. Access to the area around the buoy area would not be restricted. Signage would be installed advising of the dangers associated with the equipment. Operation of the system is expected to produce a continuous acoustical output similar to low-grade noise associated with light to normal ship traffic. At the proposed distance from shore, visual impacts by the buoy mast assembly above the waterline would not be significant.

ECONOMIC CONSIDERATIONS

Cost estimates of energy produced by WECs are dependent on many physical factors, such as system design, wave energy power, water depth, distance from shore, and ocean floor characteristics. Economic factors, such as assumptions on discount rate, cost reductions from a maturing technology, and tax incentives, are also critical. A detailed evaluation of potential wave energy development in the U.S. coastal areas has been conducted, taking into account variability in these factors (Bedard et al. 2005). The resulting cost estimate of electricity from the first commercial-scale facilities in the California, Hawaii, Oregon, and Massachusetts offshore regions with relatively high wave energy was in the range of \$0.09 to \$0.11/kWh, after tax incentives.

These facilities are very capital intensive, and these costs currently have a high degree of uncertainty. For example, capital investment cost estimates for the applications noted above range from \$4,000 to \$15,000/kW, suggesting that significant breakthroughs in capital cost would be needed to make this technology cost competitive.

SUMMARY

The offshore ocean wave energy resource, as a derivative form of solar energy, has considerable potential for making a significant contribution to the alternative usable energy supply. The total average wave energy at a depth of 60 m off the U.S. coastlines, including Alaska and Hawaii, has been estimated at 2,100 TWh/yr. In the past several decades, various designs have been developed and tested to capture this energy resource, and several are now moving toward commercial prototype testing. On the basis of currently available empirical information, the environmental impacts are expected to be small; however, as with any emerging technology, unknowns still exist with respect to environmental impacts, and careful monitoring and assessment are required.

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