FEATURE: BIOENGINEERING

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Potential Impacts of Hydrokinetic and Wave Energy Conversion Technologies on Aquatic Environments

ABSTRACT: A new generation of hydropower technologies, the kinetic hydro and wave energy conversion devices, offers the possibility of generating electricity from the movements of water, without the need for dams and diversions. The Energy Policy Act of 2005 encouraged the development of these sources of renewable energy in the United States, and there is growing interest in deploying them globally. The technologies that would extract electricity from free-flowing streams, estuaries, and oceans have not been widely tested. Consequently, the U.S. Department of Energy convened a workshop to (1) identify the varieties of hydrokinetic energy and wave energy conversion devices and their stages of development, (2) identify where these technologies can best operate, (3) identify the potential environmental issues associated with these technologies and possible mitigation measures, and (4) develop a list of research needs and/or practical solutions to address unresolved environmental issues. We review the results of that workshop, focusing on potential effects on freshwater, estuarine, and marine ecosystems, and we describe recent national and international developments.

Impactos potenciales en los ambientes acuáticos por utilizar energía hidrocinética y de olas

RESUMEN: Una nueva generación de tecnología hidrocinética y la transformación de la energía derivada de las olas naturales permiten derivar electricidad a partir del movimiento del agua sin alterar su cauce natural. En los Estados Unidos de América la Ley de Política de Energía aprobada en el 2005 promueve el desarrollo de este tipo de tecnología de producción de energía renovable y en todo el mundo hay un creciente interés por impulsarla. Este tipo de tecnología que podría extraer energía de las corrientes de los ríos, estuarios y océanos no ha sido evaluada. Consecuentemente, el Departamento de Energía de los Estados Unidos de América organizó un taller de trabajo para (1) identificar los diferentes equipos que se utilizan para la producción de energía extraída del movimiento del agua y su grado de desarrollo, (2) identificar los mejores lugares para aplicar dicha tecnología, (3) identificar los impactos potenciales y medidas de mitigación asociadas a su uso, y (4) enlistar las necesidades de investigación y soluciones prácticas aplicables a tópicos ambientales. Nosotros revisamos los resultados del taller de trabajo, enfocándonos en los impactos potenciales sobre los ecosistemas fluviales, estuarinos y marinos y describimos los avances de investigación nacional e internacional.

Conventional hydroelectric projects, with dams and reservoirs, are used all over the world to produce renewable energy. In the United States, conventional hydropower supplies 7% of the nation's electricity. The value of hydropower and other renewable energy sources is seen in renewed appreciation in light of increasing concerns about the effects of fossil fuel and biomass combustion on carbon dioxide levels in the atmosphere and global climate change. However, the ability of conventional hydropower to meet our increasing energy demands is limited, owing to a variety of environmental concerns, including degradation of fish passage, water quality, and aquatic and terrestrial habitats. It is unlikely that many new hydropower dams will be built in the United States, and there is increasing interest in removing older dams in order to restore free-flowing rivers. Nevertheless, hydropower still has a future on the U.S. and international scenes because considerable energy associated with the motions of water could be tapped by new, unconventional hydropower technologies. For example, Hall et al. (2004) estimated that as much as 3,400 MW of electricity generation potential could be exploited in U.S. rivers by small, unconventional systems such as free-flow (damless) turbines. Other estimates of the kinetic hydro potential of rivers, based on distribution of water velocities rather than stream flows, suggest much greater values. By comparison, a nuclear power plant or a large hydropower dam has a generating capacity of about 1,000 MW; most hydropower plants in the United States range from 10 to 1,000 MW in capacity

The resource potential of estuaries and ocean waters is also large. The Electric Power Research Institute (EPRI) has estimated that the annual average incident wave energy at a 60 m depth off the U.S. coastline is 2,100 TeraWatt hours per year, much of it on the West Coast (Bedard 2005a). This is equivalent to more than half of the net generation of electricity in the United States from all sources in 2004 (EIA 2006). New wave energy technologies have generated growing interest in Europe and Asia. Technologies that convert kinetic or ocean energy to electricity are being deployed in or planned for Australia, Korea, Portugal, Norway, Denmark, Russia, Sweden, and Scotland. Recent ocean energy research activities funded by the European Commission (EC) are described in EC (2006).

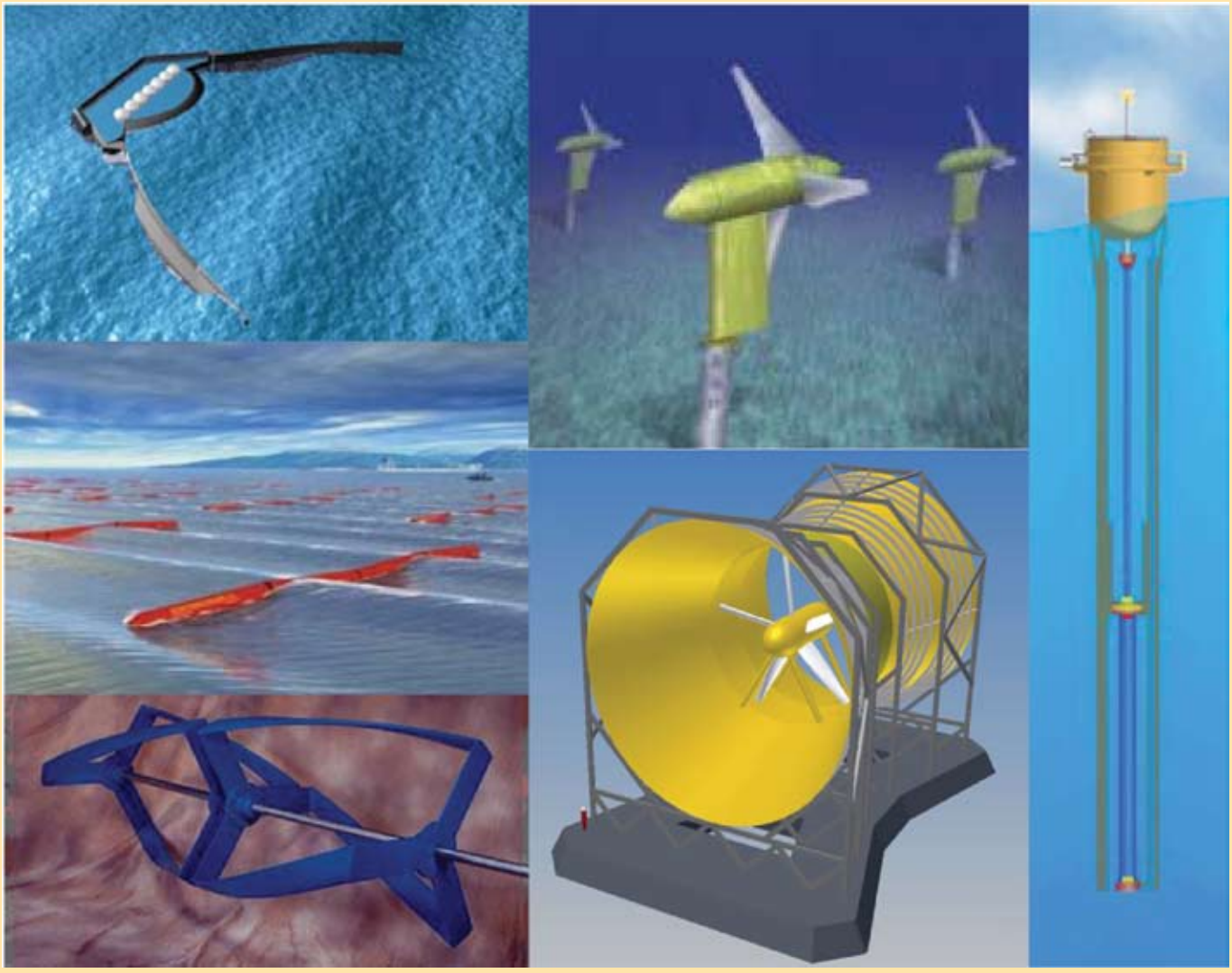
Interest in these novel hydropower technologies is growing in the United States as well. For example, Verdant Power has begun deploying underwater horizontal axis turbines in the East River in New York City as part of its Roosevelt Island Tidal Energy (RITE) project. In the summer of 2006, the Public Utility District No. 1 of Snohomish County, Washington, filed preliminary applications with the Federal Energy Regulatory Commission (FERC) to study seven sites in Puget Sound for tidal energy development (www.snopud.com). In response to the increasing numbers of permit applications, FERC held a technical conference in Washington, DC on 6 December 2006 to discuss the status of instream and ocean-based hydroelectric technologies (wave, tidal, and current) and to explore the environmental, financial, and regulatory issues related to the development of these new technologies. The U.S. Energy Policy Act of 2005 (EPAct) contains a number of provisions designed to encourage the production of renewable energy from kinetic hydro and ocean energy sources. It recognized both hydroelectric power and ocean energy (tidal, wave, current, and thermal) as forms of renewable energy, and set requirements for the federal government to purchase not less than 7.5% of its electricity from renewable sources by 2013. Section 388 of EPAct grants the Department of Interior's Minerals Management Service (MMS) responsibilities over offshore renewable energy and related uses on the Outer Continental Shelf (OCS). The MMS will grant leases, easements, or rights-of-way for renewable energy-related uses on federal OCS lands, act as a lead agency for coordinating the permitting process with other federal agencies, and monitor and regulate those renewable energy production facilities. MMS released a draft programmatic environmental impact statement in March 2007 (http:// ocsenergy.anl.gov/documents/index.cfm) to help anticipate significant issues, alternatives, and mitigation measures associated with the new Alternate Energy and Alternative Use Program. Further, EPAct Section 931 authorizes the U.S. Department of Energy to conduct research, development, demonstration, and commercial application programs for a variety of renewable energy technologies, including kinetic hydro turbines and ocean wave energy.

The technologies that would extract electricity from free-flowing streams, estuaries, and oceans have not been widely tested; indeed, many are little more than ideas from the drawing board. Consequently, the U.S. Department of Energy's (DOE) Wind and Hydropower Technologies Program convened a workshop in October 2005 to ascertain the technical and environmental issues associated with hydrokinetic and wave energy conversion devices. Representatives from private business, government (regulatory and resource agencies), and non-government organizations met for three days and shared ideas to identify the issues and develop lists of research needs. The proceedings of the workshop are available at: http://hydropower.inel.gov/hydrokinetic_wave/index.shtml. In this article, we focus on the potential impacts to aquatic organisms and ecosystems that were identified by the workshop participants and discuss how uncertainties about these impacts might be addressed.

Descriptions and illustrations of these novel renewable energy technologies can be found in the DOE workshop proceedings and other compilations (e.g., Figure 1, Table 1, and www.epri.com/oceanenergy). There are numerous ways to categorize these new devices, but they can most simply be divided into two classes: rotating machines and wave energy converters (Bedard 2005b). Rotating machines can be compared to wind turbines—a rotor spins in response to the movements of river or ocean currents, the rotational speed being proportional to the velocity of the fluid. The rotor may be encased in a duct that channels the flow (e.g., the Rotech Tidal Turbine; www.lunarenergy.co.uk) or open like a wind turbine (e.g., the Verdant horizontal axial turbine; www.verdantpower.com). Further, the rotor may be characterized by conventional "propeller-type" blades or helical blades (www.gcktechnology.com/GCK). Whether installed in rivers, estuaries, or in the open ocean, rotating machines convert kinetic energy (the energy associated with a body of water because of its motion) into electricity.

On the other hand, many of the wave energy technologies convert hydrostatic energy, the energy possessed by a body of water because of its elevation (i.e., head) relative to a reference point. These devices oscillate based on changes in the height of ocean waves (head or elevation changes). Several leading concepts are displayed in Figure 1. For example, AquaEnergy's AquaBuOY has been proposed for

Figure 1. Examples of kinetic and ocean energy conversion technologies considered at the DOE workshop. Clockwise from upper left: the Wave Dragon, Verdant Power's horizontal axis turbine, AquaEnergy's AquaBuOY, Lunar Energy's ducted tidal turbine, the Gorlov helical turbine, and Ocean Power Delivery's Pelamis. See the text for web links and descriptions of the devices.



deployment at Makah Bay, Washington (http://finavera.com). The AquaBuOY is a floating structure, moored to the ocean bottom, which uses the vertical motions of ocean waves to drive a pump that moves seawater over a turbine. Another example of a "point absorber," where a floating buoy responds to movements of the sea surface, is the Power Buoy (www.oceanpowertechnologies.com). Ocean Power Delivery's Pelamis consists of a series of semi-submerged cylinders linked by hinged joints (www.oceanpd.com). The motions of the cylinders relative to each other are resisted by hydraulic rams, which move high-pressure oil through hydraulic motors, which in turn drive electrical generators contained within the cylinders. Pelamis was tested in Scotland and is being deployed in Portugal. Overtopping devices such as the Wave Dragon (www.wavedragon.net), incorporate elements from traditional hydroelectric power plants in an offshore floating platform. Water is elevated into a floating reservoir and then passes down through low-head hydropower turbines. The Wave Dragon concept, essentially a floating hydroelectric dam, was tested off the coast of Wales, and has received further research and development funding from the European Union.

SUMMARY OF ENVIRONMENTAL ISSUES AND UNCERTAINTIES

Table 2 lists the potential environmental impacts of kinetic hydro and ocean energy conversion technologies identified by workshop participants. Most of the environmental issues will need to be addressed by all of the technologies considered at the workshop. For example, all of these machines will need to be secured to the river or ocean bottom in some way, either by pilings driven into the sediments or by anchors and mooring cables. Disruption of the sediments during installation will alter the bottom habitats and may increase turbidity or release buried contaminants. Sediment disruption may be a temporary event associated with installation, or may continue during operation owing to movements of the rotors or of unsecured power and mooring cables. Because these

Table 1. Generalized list of hydrokinetic and ocean wave energy technologies considered in the DOE Workshop.

General type	Example
Horizontal axis (reaction) turbine	Verdant horizontal axis turbine
Cross flow (helical) turbine	Gorlov turbine
Open center turbine	OpenHydro open center turbine
Ducted turbine	Rotech tidal turbine VA Tech Hydromatrix
Point absorber	Aqua Energy AquaBuoy Ocean Power Technology PowerBuOYy
Attenuator	Ocean Power Delivery Pelamis
Terminator	Energetech oscillating water column
Overtopping wave	Wave Dragon

Table 2. Description of the aquatic environmental issues that were identified by DOE Workshop participants.

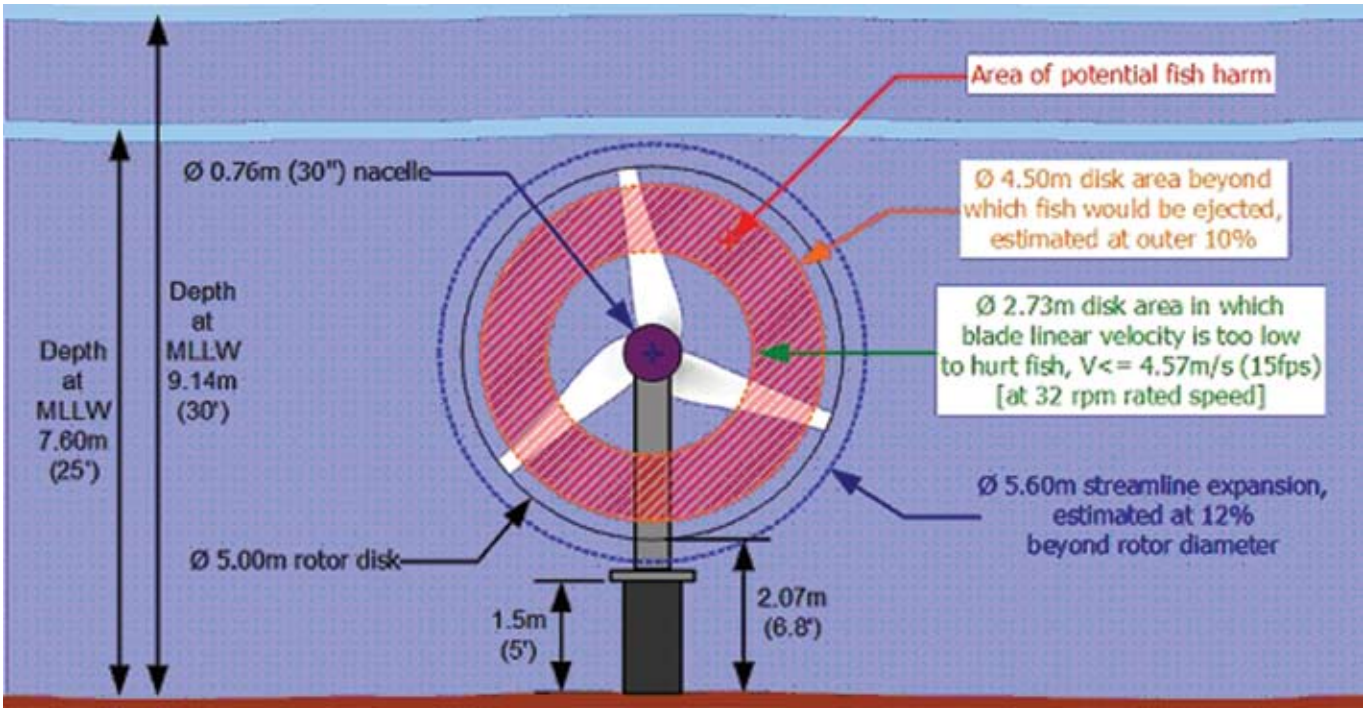
Environmental issue	Brief description of the issue
Alteration of river/ocean bottom habitats	Bottom habitats will be altered by securing the device to the bottom and running power cables to the shoreline. Moving parts (rotors) and mooring systems could affect bottom habitat during operation. Device may create structural habitat in open waters. Structures may obstruct movements/migrations of aquatic animals.
Suspension of sediments and contaminants	Deployment and operation may disrupt sediments and buried contaminants and increase turbidity. Erosion and scour may occur around anchors, cables, and other structures.
Alteration of hydraulics and hydrologic regimes	Movement of the devices will cause localized shear stresses and turbulence that may be damaging to aquatic organisms. On larger scales, extraction of energy from the currents may reduce the ability of streams to transport sediment and debris, cause deposition of suspended sediments and thereby alter bottom habitats.
Strike	Fish and other aquatic organisms, diving birds, and mammals may be struck by moving parts of the devices (e.g., rotors). Large mobile animals may become entangled in submerged cables.
Impingement on screens	Screens used to protect the machine or to reduce strike could themselves injure aquatic animals.
Effects of electromagnetic fields	Electromagnetic fields associated with all of these devices may attract, deter, or injure aquatic animals.
Toxicity of paints and other chemicals	Paints, cleaners, hydraulic fluids and chemicals used to control biofouling may be toxic to aquatic plants and animals.
Noise	Noise during construction and operations may attract, deter, or injure aquatic animals.
Effects of multiple units	Effects on hydrologic regimes, sediment dynamics, and strike determined for single machines may be very different than a full deployment of dozens or hundreds of machines.

devices extract energy from moving water or tides, they will alter local hydraulics. Shear stresses and turbulence will be created near rotors that may injure aquatic organisms or scour nearby sediments. On a larger scale, dozens or hundreds of these machines may alter the hydrologic regime and cause large areas of sediment scour or deposition. The significance of these impacts will depend on the design, size, and numbers of the devices and the method of their deployment, as well as the site-specific characteristics of the bottom sediments. Further, the potential negative impacts need to be considered in the context of other existing uses and stresses on these aquatic ecosystems (i.e., cumulative effects).

Similarly, effects of electromagnetic fields, noise during construction and operation, and the toxicity of paints and other chemicals will need to be addressed by all of these technologies. Technically, these issues should not be difficult to resolve. For example, the strength of magnetic fields can be measured for prototype machines and compared to levels that are known to affect animals. Similarly, the intensity and frequency of noise produced by the machines can be assessed by comparing measurements of prototypes to noise from other aquatic sources and to information in the literature about underwater sounds that injure, frighten, or attract aquatic animals. Shielding might be employed to reduce excessive noise and electromagnetic fields. The effects of chemicals can be controlled by using appropriate, non-toxic paints and ensuring that hydraulic fluids are well sealed within the machine.

Blade strike and impingement on protective screens are likely to be issues only for rotating machines. Fish, aquatic reptiles and mammals, and diving birds may be struck by the rapidly turning rotor and suffer injury or mortality. Screens used to exclude aquatic animals from the machine will reduce power production and may themselves cause injury if the

Figure 2. Hypothetical zone of potential damaging strike associated with a submerged free-flow (rotating) turbine. This is based on the assumption that the risk of strike injury is lower near the hub (where rotational velocity is low) and near the tip (where a fish can escape to the side) than in the mid-blade region. Source: Coutant and Cada (2005).



organism is impinged against the screen. The seriousness of strike is related to the animal's swimming ability and sensitivity to injury, and to the part of the rotor that the animal strikes (Figure 2). The rotor blade has a much higher velocity near the tip than near the hub, and the force of strike is expected to be proportional to the velocity. As was frequently noted at the workshop, because of design similarities between rotating kinetic hydro turbines and the enclosed runners in conventional hydroelectric turbines, existing literature on fish passage effects can be consulted to make preliminary estimates of the seriousness of damage to fish from strike, as well as other hydraulic stresses (pressure changes, shear stresses, and turbulence that occur near the rotor; see, for example, Cada et al. 1997; Ploskey and Carlson 2004). Compared to conventional hydroelectric turbines, some kinetic hydro designs have an unenclosed rotor and slower rotation rates, which could reduce the risk from strike.

Wave energy devices create structures in the open ocean. The effects of multiple surface structures and associated cables covering a sizeable area of the ocean may be negative, for example if they interfere with movements of whales and other large animals. Or they may be beneficial, serving as fish attracting devices, preserving areas of the ocean from commercial harvest, and providing roosting sites for birds and haul out sites for seals and sea lions. Colonization of the structures by marine organisms is likely to have negative consequences for maintenance and electricity generation and unknown environmental effects. The extraction of wave energy by these devices may alter sediment transport and thereby affect local beach geomorphology, benthic habitats, and intertidal ecology.

Beyond the environmental assessments of individual machines, the workshop participants expressed concerns about both multiple-unit deployments and the cumulative impacts of energy developments when added to other stresses on aquatic systems. In order for these technologies to make a significant contribution to our electricity supply, larger devices or installations of many small units will be needed. For example, Snohomish County Public Utility District has applied for a preliminary permit to investigate the possibility of installing 450 Tidal In Stream Energy Conversion (TISEC) devices, each with a 20-m-diameter rotating propeller blade, at a single site in Puget Sound, Washington (71 FR 37071; 29 June 2006). Williams (2005) suggested that 3,000 to 4,000 open center turbines could be deployed in the Gulf Stream to provide a generation potential of 10,000 MW of electricity. Impacts to bottom habitats, hydrology, or strike that are inconsequential for one or a few units may become significant if energy farms exploit large areas in a river, estuary, or nearshore ocean. By extracting energy from currents, very large installations might conceivably influence large scale ocean circulation patterns. It may not be easy to extrapolate effects from small to large numbers of units because the complicated interactions between water motions and turbines depend on placement of the machines (proximity to each other) as well as local hydraulic conditions. Hydraulic models will likely be needed to predict accurately the effects of multiple units. The deployment of turbines will add to existing environmental stresses and cumulative effects. In rivers, the effects of kinetic turbines would occur in the context of other impacts associated with boat traffic, water withdrawals, and discharges. In the ocean, energy developments must compete with aquaculture, offshore wind, gas and oil platforms, defense-related activities, mining, merchant shipping, recreational and commercial fishing, and recreational boating (Ogden 2005). Structures associated with an ocean energy farm could act as fish attracting devices and, by restricting commercial fishing in the area, conceivably have positive effects on aquatic communities. Perhaps the most sensitive habitats to cumulative impacts are

the estuaries, highly complex and productive ecosystems that are already subject to anthropogenic alteration from water diversion, habitat conversion, pollution, dredging, and urbanization (Swanson 2005). As with other cumulative effects, the contribution of new energy development to overall impacts on aquatic resources could be additive, synergistic, or offsetting.

RESOLUTION OF ENVIRONMENTAL ISSUES

Like the machines themselves, the research needed to understand and minimize environmental impacts can be divided into two classes: site-specific and general. Site-specific research would be conducted by the manufacturer/developer and might include impacts of particular design details (e.g., comparison of the toxicity of different paints or lubricating fluids; comparisons of noise measurements to tolerances of local fauna) or the effects on a particular river or estuary that is proposed for development (e.g., sediment cores, modeling of multi-unit placement relative to a specific bottom profile).

On the other hand, many environmental research questions of general interest might best be addressed by collaborative groups, and the results made freely available to all. Collaborative studies could include experiments to understand the mechanisms of impacts of kinetic hydro and wave conversion devices (e.g., the differences in frequency and severity of strike in ducted vs. unducted rotors or different rotor blade shapes; advanced physical and computational models of alternative multi-unit deployment strategies). Individual developers rarely have the resources to carry out this general research on their own, but the information that comes from such studies is often of interest to a wide audience seeking to refine their designs and operations in order to minimize environmental impacts. The results of collaborative efforts are much more likely to influence decision making if the studies are funded, designed, conducted, and analyzed by a broad group representing all interests.

The workshop participants considered several models for collaborative research. For example, EPRI's Ocean Energy Research Program has brought together agencies from coastal states, utilities, technology developers, research institutions, and other parties to demonstrate the feasibility of wave power (Bedard 2005a). The program's initial activities have focused on estimating power production, performing economic assessments, and identifying potential sites for conceptual wave energy plants; environmental issues have not been rigorously examined. The European Marine Energy Centre (EMEC) was established in Orkney, Great Britain, to conduct independent tests of marine energy technologies (Griffiths 2005; EMEC 2005). Construction of the center began in 2002 with funding from public agencies. Developers of wave or tidal energy conversion devices will then provide funds to the center for standardized, independent testing. EMEC has begun accepting wave and tidal devices; at present, their standardized tests and measurements are focused on verifying engineering performance. Environmental monitoring consists of recording sightings of marine mammals, but this is intended to ensure that there are no adverse effects from operation of the test site, rather than environmental research per se. Eventually EMEC hopes to help developers certify their machines for environmental standards as well. A U.S. Marine Energy Center headquartered in Oregon has been proposed (Rhinefrank 2005). Like EMEC, it would provide a standardized, controlled environment where developers could test their wave energy conversion devices. However, as with

the EPRI and EMEC efforts, the emphasis initially would be on characterizing engineering performance rather than studying potential environmental issues. Sundberg and Langhamer (2005) described the marine environmental studies that will be performed on a wave power project at Islandsberg, off the coast of Sweden. When fully built out, up to 40 buoys and 10 wave power devices will be deployed, covering an area of 40,000 m^2. Environmental studies planned for the 2008-2014 time frame include invertebrate colonization, larval recruitment, fish attraction, effects of anti-biofouling coatings, and use of the buoys by birds and seals.

The workshop participants agreed that an EMEC-like facility where environmental studies could be carried out by independent investigators and the results accessible to all would be a great value to the development of kinetic hydro and wave energy technologies. Alternatively, the needed information might be developed through a research program that systematically explores the most difficult environmental issues, as has been done for conventional hydropower turbines in the DOE's Advanced Hydropower Turbine System Program (http://hydropower.inel.gov). A research program might best identify widely applicable impact minimization measures and possible beneficial effects on the environment (e.g., creation of new structural habitat and de facto protected areas). In the absence of such general, nationwide programs, adequate site-specific monitoring, focusing on the potential issues raised at the workshop, will be essential to ensuring that large energy production fields do not have unacceptable environmental impacts.

All workshop participants agreed that adequate understanding of environmental effects by regulators and the public is essential to acceptance of their technologies. The developers emphasized that proportional response from regulators is needed – small deployments are likely to have small, localized impacts. Small-scale monitoring programs will help resolve issues of individual installations and, if results are disseminated, will help focus the more extensive monitoring that will be needed for large deployments. At this early stage of technology development, both regulators and developers need to be open to an adaptive management approach, in which environmental monitoring and phased deployment are adjusted to reflect the findings of the previous monitoring (as is planned for the Roosevelt Island Tidal Project in New York City; Coutant and Cada 2005). The process of collecting environmental effects data should be guided by what is needed to achieve the ultimate goal of full-sized, multi-unit projects. It was also pointed out that developers should realize that a "disassembly plan" may be required in the event that environmental impacts of a project cross a previously defined threshold for significant environmental impacts.

Kinetic hydro and wave energy technologies are on their way to deployment, and are likely to be just as variable in their environmental effects as they are in their design. We cannot know exactly what the impacts will be until some prototypes are installed and tested. Some of the environmental issues raised at the DOE workshop (e.g., chemicals and noise) will likely be easy to assess and mitigate. Others will require site-specific studies (e.g., scour and sediment deposition) to resolve. Still others may need considerable study and may not be easy to mitigate. The sharing of information from previous studies, both of conventional hydropower projects and new technologies, will be important to ensuring the environmentally sound development of these new renewable energy technologies. ♋

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