Assessing the Effects of Marine and Hydrokinetic Energy Development on Marine and Estuarine Resources

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Abstract

The world's oceans and estuaries offer enormous potential to meet the nation's growing demand for energy. The use of marine and hydrokinetic (MHK) devices to harness the power of wave and tidal energy could contribute significantly toward meeting federal- and state-mandated renewable energy goals while supplying a substantial amount of clean energy to coastal communities. Locations along the eastern and western coasts of the United States between 40° and 70° north latitude are ideal for MHK deployment, and recent estimates of wave and current energy resource potential in the US suggest that up to 400 terawatt hours could be generated, representing about 10% of national energy demand. Because energy derived from wave and tidal devices is highly predictable, their inclusion in our energy portfolio could help balance available sources of energy production, including hydroelectric, coal, nuclear, wind, solar, geothermal, and others.

As an emerging industry, MHK energy developers face many challenges associated with the siting, permitting, construction, and operation of pilot and commercial-scale facilities. As the industry progresses, it will be necessary not only to secure financial support and develop robust technologies capable of efficient, continued operation in harsh environments, but also to implement effective monitoring programs to evaluate long-term effects of device operation and assure resource agencies and members of the public that potential environmental impacts are understood and can be addressed.

At this time, little is known about the environmental effects of MHK energy generation at pilot- or full-scale operational scenarios. Potential effects could include changes to aquatic species behavior from exposure to electromagnetic fields or operational noise; physical interaction of marine mammals, fish, and invertebrates with operating devices or mooring cables; or changes to beach characteristics and water quality from long-term deployment of devices in coastal locations. This lack of knowledge creates a high degree of uncertainty that affects the actions of regulatory agencies, influences the opinions and concerns of stakeholder groups, affects the commitment of energy project developers and investors, and ultimately, the solvency of the industry.

To address the complexity of environmental issues associated with MHK energy, PNNL has received support from the Department of Energy Office of Energy Efficiency and Renewable Energy Waterpower Program to develop research and development that draws on the knowledge of the industry, regulators, and stakeholders. Initial research has focused on 1) the development of a knowledge management database and related environmental risk evaluation system, 2) the use of hydrodynamic models to assess the effects of energy removal on coastal systems, 3) the development of laboratory and mesocosm experiments to evaluate the effects of EMF and noise on representative marine and estuarine species, and 4) collaborative interaction with regulators and other stakeholders to facilitate ocean energy devices, including participation in coastal and marine spatial planning activities.

In this paper, we describe our approach for initial laboratory investigations to evaluate potential environmental effects of EMFs on aquatic resources. Testing will be conducted on species that are a) easily procured and cultured, b) ecologically, commercially, recreationally or culturally valuable, and c) reasonable surrogates for threatened or endangered species. Biological endpoints of interest are those that provide compelling evidence of magnetic field detection and have a nexus to individual, community, or population-level effects. Through laboratory, mesocosm, and limited field testing, we hope to reduce the uncertainly associated with the development of ocean energy resources, and gain regulatory and stakeholder acceptance. We believe this is the best approach for moving the science forward and provides the best opportunity for successfully applying this technology toward meeting our country's renewable energy needs.

During the project, the team will work closely with two other national laboratories (Sandia and Oak Ridge), the Northwest National Marine Renewable Energy Center at University of Washington and Oregon State University, and Pacific Energy Ventures.

I. INTRODUCTION

There is a compelling need to develop alternative forms of electrical energy from renewable sources. Currently, 24 states and the District of Columbia have created renewable portfolio standards that establish the amount of energy that must come from renewable sources. Many of the state standards are quite ambitious, requiring 8% to 40% of energy from renewable sources within one to two decades [1]. Because states account for over 50% of the electricity used in the United States, adherence to and implementation of these standards will require significant investments in new energy technology, comprehensive environmental reviews and permitting actions, cooperative efforts among federal and state regulatory agencies, stakeholder buy-in, and significant financial investments. For states located along the Pacific and Atlantic coasts, electrical power generation from wave and tidal action represents an enormous potential renewable resource that could enable them to meet their portfolio standards. Based on a 2007 assessment, the Electrical Power Research Institute (EPRI) estimates that US wave and current energy potential is about 400 terawatt hours per year (TWH/yr), representing approximately 10% of the nation's energy needs [2]. Similar resource estimates exist for coastal locations in other parts of the world, and field-testing of wave and tidal systems are planned or are already occurring in Portugal, United Kingdom, Sweden, Spain, Norway, Denmark, Ireland, Japan, Australia, and Canada. Although there are no full-scale marine and hydrokinetic (MHK) device arrays operating in the United States, pilot-scale testing is planned or is occurring in a variety of locations, including Puget Sound, Washington, and coastal regions in Texas, New Jersey, and Hawaii [3].

The development of MHK energy represents significant environmental challenges that must be addressed before key investments are made in pilot-scale and full-scale operations. These challenges have been the subject of numerous technical workshops [4, 5] and a variety of comprehensive technical reviews or papers from United States and internationally [3, 6-9]. Potential environmental effects associated with MHK devices generally fall into seven categories (Table 1) relative to interactions with the physical environment, direct and indirect effects on aquatic resources, and the cumulative effect of multiple stressors (or multiple devices or arrays) on aquatic ecosystems. Potential receptors include benthic invertebrates, fish, seabirds, sea turtles, marine mammals, and key attributes of ecosystem structure and function (Table 2). In this paper, we will focus on the potential environmental effects of electromagnetic fields (EMF) on aquatic resources. EMFs are of particular interest because they will be present regardless of MHK design or location, and may exert direct effects (e.g., changes in fecundity) or indirect effects (e.g., interference with navigation and migration, predator detection and avoidance, other behavioral changes) on aquatic organisms. If present, these direct or indirect effects could result in detectible changes at individual, community, or population scales, or contribute to the cumulative effects that influence key environmental attributes.

TABLE 1
ENVIRONMENTAL CONCERNS AND POTENTIAL EFFECTS OF MARINE AND HYDROKINETIC DEVICE OPERATION
(ADAPTED FROM CADA ET AL., 2007 [7])

Environmental Concern	Potential Effects
Alteration of marine or estuarine benthic habitats	• Direct effects by the physical presence of mooring devices and transmission cables • Indirect effects to water exchange or water quality associated with device operation and energy removal • Obstruction to organism movement or migration; changes to behavior, benthic diversity, or abundance due to "reef effects" from the devices or infrastructure
Energy removal associated with device operation	• Increase or reduction of natural sediment transport functions, resulting in deposition or erosion/scour • Changes to water quality from altered circulation patterns
Physical interaction with MHK devices or moorings	• Physical injury to marine mammals, fish, diving birds, or larval forms due to strike, unnatural shear forces, entanglement, impingement, or entrainment
Toxicity of antifouling coatings	• Increase in contaminant concentrations in water, sediment, or biota from toxic coatings on devices
Noise	• Injury or change in behavior or migratory habits of sensitive aquatic species • Interruption of communication or navigation in marine mammals, birds, or fish
Electromagnetic fields	• Changes in migratory habits • Interference with ability to detect prey or avoid predators • Changes in feeding or mating behavior • Indirect chronic effects that influence growth or reproduction
Cumulative effects	• Changes to the natural structure and function of aquatic ecosystems, resulting in changes to species abundance and diversity, nearshore geomorphology, sediment transport, and water quality

TABLE 2
EXAMPLES OF RECEPTOR CATEGORIES AND SUSCEPTIBILITY

Receptor Category	Susceptibility
Benthic invertebrates	Changes to species behavior regulating feeding, mating, or predator/prey detections leading to changes in abundance or diversity; acute or chronic toxicity from coatings
Fish	Attraction to surface or subsurface structures, changes to predator-prey dynamics, interference with migratory patterns due to noise or EMF emissions
Seabirds	Collision of diving birds with turbine blades, surface strikes on wave buoys, entanglement in mooring lines, acoustic effects affecting navigation
Sea turtles	Entanglement in mooring lines, interference with navigation from EMF emissions.
Marine mammals	Interaction with turbine blades, confusion from acoustic output of turbine, entanglement in mooring lines, interference with migratory routes, interference with communication
Ecosystems	Removal of energy from marine and estuarine systems resulting in changes to water quality, sediment transport, nearshore geomorphology and food web dynamics

II. POTENTIAL EFFECTS OF ELECTROMAGNETIC FIELDS ON MARINE AND ESTUARINE SPECIES

Although all MHK devices will generate some EMFs from device operation or electrical transmission cables (Fig. 1), the strength and duration of the fields is dependent on the device design, operational characteristics, level of shielding employed to reduce emissions, and the number of arrays deployed at a given location. MHK power cables generate both an electric field (E Field) and a magnetic field (B Field), as shown in Fig. 2 [9]. Although E Fields are expected to be completely shielded in industry-standard power cables, the cables provide only limited shielding of B Fields, which can result in induced electric fields (iE) in the cable systems independent of burial [9] (Fig. 1).

Compared with the vast array of scientific studies on the environmental effects of contaminants on aquatic organisms, there is a paucity of peer-reviewed scientific information on EMF effects. Available information is primarily from Europe and Japan, where MHK and offshore wind research, development, and environmental permitting has been occurring for over the past two decades. It is generally agreed that many marine and estuarine fish species, including sharks, skates, rays, eels, tuna, and salmonids, contain small amounts of magnetic material in their bodies, implying the capacity to detect magnetic fields [9]. Magnetic orientation and navigation in marine turtles, lobster, and mollusks are also believed to occur, providing these species with “magnetic maps” for navigation [10]. It is uncertain to what degree these organisms rely on the earth’s magnetic fields; effects may occur if these static fields are altered by MHK devices and power cables.

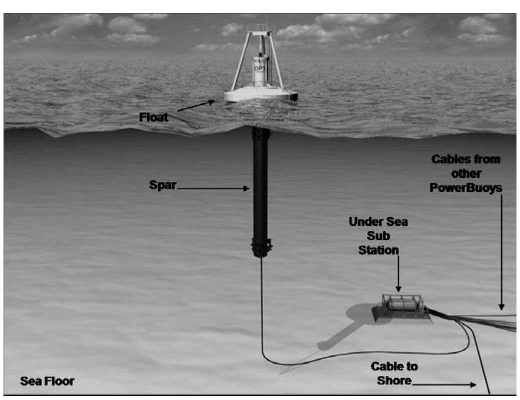

Fig. 1 Representative MHK device, showing power cable configuration.

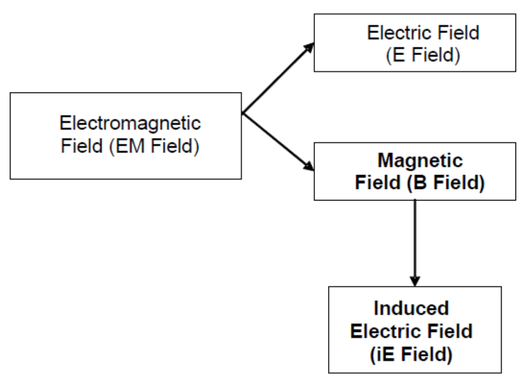

Fig. 2 Relationship of electric, magnetic, and induced fields.

Long-term exposure of prawns, crab, isopods, mussels, and flounder to a static magnetic field of 3.7 milli Tesla (mT) by Bochert and Zettler [11] showed no differences between exposed and control organisms. This field strength is approximately 70 times greater than natural geomagnetic values of approximately 50 micro Tessla, but theoretically possible near cables using high voltage direct current [11]. Studies by Yano et al. [12] with chum salmon suggested that the presence of a 6 gauss (0.6 mT) artificial magnetic field did not noticeably affect horizontal or vertical movements, but may have influenced swimming speed. Other studies designed to evaluate growth and reproduction in zebrafish (Skauli et al.) [13] and guppies by Brewer et al. [14] suggest that magnetic fields ranging from 1 to 50 mT may influence spawning, gestation period, or hatching. Clearly, the available information is ambiguous, and raises many questions concerning the effects of EMF exposure and implications to individual organism health and fitness as well as the influence at community and population scales.

III. Experimental Design for Laboratory Exposures

Initial laboratory investigations will be conducted on fish and invertebrate species that are a) easily procured, collected, and/or cultured, b) ecologically, commercially, recreationally, or culturally valuable, and c) reasonable surrogates for threatened or endangered species (Table 3). Biological endpoints of interest are those that provide compelling evidence of magnetic field detection and have a nexus to individual, community, or population-level effects (Table 3). Laboratory testing will be conducted using a custom-made Hemholtz coil capable of creating a uniform magnetic field of up to 3 mT within a cube measuring 30 cm on a side (Figure 3). When possible, existing biological testing protocols will be adapted for use in magnetic fields, as described below. In addition, tests will be designed to address, when possible, common test-related considerations or parameters that can confuse or confound the interpretation of biological data. These tests include, but not limited to 1) magnetic field intensity and timing, 2) duration and repetition of exposure, including circadian time influences, 3) spatial characteristics, and 4) exposure to combined EMFs, and effects of incidental exposure [15]. Initial testing will focus primarily on basic biological responses (e.g., predator-prey avoidance, behavioral cues indicating detection of EMF fields) to limited exposure durations under highly controlled conditions. As testing progresses and biological response is assessed, complexity may be added through expanded laboratory exposures, mesocosm experiments, and limited field investigations similar to those developed by Cowrie for MHK installations in the United Kingdom [16]. All of the fish and invertebrate species described below are amenable to laboratory mesocosm and limited field exposures.

TABLE 3
Initial Experimental Design for MHK Laboratory Tests

Fish and Invertebrate Category	Lifestage	Test Endpoint(s)	Environmental Relevance
Salmonids	Adults, juveniles	Avoidance, attraction, habituation	Predator/prey relationships and changes to migration affect population dynamics and persistence
Salmonids	Juveniles	Gamete maturation	Individual survival and growth affects population dynamics and persistence
Halibut/Flatfish	Juveniles and larvae	Avoidance, attraction, habituation	Changes to predator/prey relationships affect population dynamics and persistence
Halibut/Flatfish	Juvenile	Time to eye migration (larval transformation)	Survival and growth affect population dynamics and persistence
Rockfish	Adults or juveniles	Avoidance, attraction, habituation	Changes to predator/prey relationships population dynamics and persistence
Rockfish	Gravid females	Survival and growth of live-born young	Individual survival and growth influences population persistence
Dungeness crab	Adult	Antennular flicking rate change and food detection	Changes to foraging and movement patterns affect distribution and abundance
Dungeness crab	Juveniles, adults	Avoidance or attraction to EMF	Changes in mating, foraging, migration, predator/prey interactions affect survival, distribution, and abundance

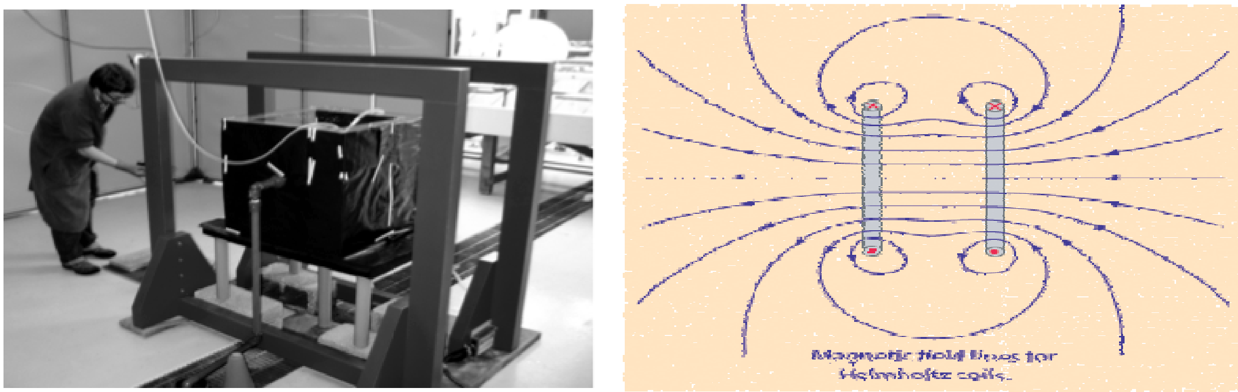

Fig. 3 Helholtz coil experimental system showing orientation of the coils (left) and magnetic fields (right).

A.   Salmonid Tests

Juvenile coho salmon (*Oncorhynchus kisutch*) and rainbow trout (*O. mykiss*) were chosen for laboratory evaluations because they are representative of mid-water species that are ecologically, commercially, recreationally, and culturally important in both marine and freshwater environments and are likely to encounter MHK devices or transmission cables at some stage in their life cycle. For both species, initial tests will focus on whether an “alarm response” is inhibited or enhanced by the presence of an EMF. Testing protocols will be adapted from similar experiments conducted to evaluate the effect of exposure to organic or inorganic chemicals [17-19]. Test design will include exposures to a uniform 3-mT field using the Hemholtz coil system and concurrent control exposures at background magnetic field strengths. If a significant response is observed, additional experiments will be conducted using a range of EMFs to establish an exposure-response relationship. Subsequent experiments will investigate the effect of EMFs on organism survival and growth. Because predator recognition, survival, and growth are key factors in salmonid survival, these endpoints will provide valuable information on potential effects associated with population effects from EMF exposure.

B.   Halibut/Flatfish Tests

Halibut (flatfish) are bottom-dwelling organisms that are ecologically, recreationally, and commercially important along both Pacific and Atlantic coastlines. Two species of larval halibut will be evaluated in the laboratory: California halibut (*Paralichthys californicus*) and Atlantic halibut (*Hippoglossus hippoglossus*). Both have been the subjects of extensive laboratory evaluations related to marine aquaculture, and both are likely to encounter MHK devices or transmission cables during their life cycle. Initial laboratory testing will evaluate effects of EMFs on feeding behavior, metamorphosis, survival, and ability to detect predators. Test design will draw from scientific literature describing morphological development [20, 21], abnormalities in eye migration (metamorphosis) observed in fish hatcheries [22], predator-avoidance strategies [23], and feeding strategies [22, 24]. These endpoints are considered environmentally relevant because they provide an assessment of how the presence of EMF could influence distribution or survival of these species.

C.   Rockfish Tests

Rockfish occupy mid-water and near bottom habitats, often seeking cover from natural and man-made structures. Thus, many rockfish species are expected to be attracted to and regularly interact with MKH devices and cables. Rockfish are an important part of marine and estuarine food webs as well as recreational fisheries, and some species of rockfish are listed as threatened or endangered or known to be in significant decline. Laboratory studies will focus on surrogate species that are common to marine and estuarine habitats. Preliminary tests will evaluate avoidance, attraction, and habituation endpoints. Because some species brood and bear live young, chronic exposure of females to EMF followed by observation of growth and survival of young could provide important information on community and population-level effects.

C. Dungeness Crab Tests

The Dungeness crab, *Cancer magister*, represents a bottom-dwelling invertebrate that is ecologically, commercially, recreationally, and culturally important to coastal areas of the western United States. Because this crab is common to both coastal and estuarine nearshore environments, they are likely to encounter MHK transmission cables during their life cycle. Initial laboratory testing will focus on evaluating antennular flicking rate- a behavioral cue that has been successfully used to demonstrate detection of trace chemical cues in the environment [25-27]. Subsequent studies will focus on how static or variable magnetic fields may induce an avoidance or attraction response leading to altered feeding behavior or predator/prey interactions. These behavioral responses could influence crab distribution or density at local or regional scales.

IV. CONCLUSIONS

The intent of this research is to expand the state of the knowledge related to the effects of EMF exposure in marine and estuarine species. By building on the work of others, adapting accepted biological testing protocols for use in short- and long-term assessments, and building sequentially from simple to complex responses and study design, we hope to reduce the uncertainly associated with this new energy resource and gain regulatory and stakeholder acceptance. Because it is logistically and financially impossible to evaluate all potentially sensitive aquatic organisms, especially those that are listed as threatened or endangered or those not amenable to testing, surrogate species will be employed to evaluate environmental effects. If species selection and exposure regimes are relevant and if potential confounding factors are controlled or eliminated, it is likely that a reasonable estimate of MHK effects can be derived from laboratory, mesocosm, and limited field tests. Inclusion of regulators, industry representatives, and stakeholders early in the process will enhance our ability to apply this rapidly developing science and technology toward meeting our country's renewable energy needs.

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