ENVIRONMENTAL AND ECOLOGICAL EFFECTS OF OCEAN RENEWABLE ENERGY DEVELOPMENT

A Current Synthesis

BY GEORGE W. BOEHLERT AND ANDREW B. GILL

ABSTRACT. Marine renewable energy promises to assist in the effort to reduce carbon emissions worldwide. As with any large-scale development in the marine environment, however, it comes with uncertainty about potential environmental impacts, most of which have not been adequately evaluated—in part because many of the devices have yet to be deployed and tested. We review the nature of environmental and, more specifically, ecological effects of the development of diverse types of marine renewable energy—covering marine wind, wave, tidal, ocean current, and thermal gradient—and discuss the current state of knowledge or uncertainty on how these effects may be manifested. Many of the projected effects are common with other types of development in the marine environment; for example, additional structures lead to concerns for entanglement, habitat change, and community change. Other effects are relatively unique to marine energy conversion, and specific to the type of energy being harnessed, the individual device type, or the reduction in energy in marine systems. While many potential impacts are unavoidable but measurable, we would argue it is possible (and necessary) to minimize others through careful device development and site selection; the scale of development, however, will lead to cumulative effects that we must understand to avoid environmental impacts. Renewable energy developers, regulators, scientists, engineers, and ocean stakeholders must work together to achieve the common dual objectives of clean renewable energy and a healthy marine environment.

INTRODUCTION

Renewable energy resources may represent one of humankind's best hopes for reducing our substantial contribution to global warming (Krupp and Horn, 2008). Technology to capture the energy from wind, the sun, and biomass are all in various stages of development. In many areas of the world, marine renewable energy has great promise but many of the approaches remain to be developed to commercial standards. Energy from marine wind, tides, currents, waves, and thermal gradients may all hold immense potential for electrical energy generation. The development of the technology, however, is not without environmental and social concerns (Pelc and Fujita, 2002; Gill, 2005; Cada et al., 2007; Boehlert et al., 2008; Inger et al., 2009). Many countries require a comprehensive examination of potential environmental effects (e.g., for wave energy: Wilson and Downie, 2003; Faber Maunsell and METOC PLC, 2007; and for offshore wind: MMS, 2008). The development of various frameworks to evaluate environmental effects is underway (e.g., EquiMAR, http://www.equimar.org; Simas et al., 2009). In the United States, the Minerals Management Service (Michel et al., 2007) and Department of Energy (DOE, 2009) have instituted similar efforts. In this article, we briefly review the potential environmental effects of development of marine renewable energy on a worldwide basis.

The consideration of environmental effects is complex; the multiplicity of technologies (Bedard et al., 2010), ocean areas, and ecosystems likely for development of marine renewable energy make a comprehensive treatment impossible in a single short article. In keeping with the goals of this volume, the scope of the present article will be limited to wind, wave, tidal, current, and thermal gradient approaches in ocean renewable energy development (referred to herein as ORED, adapted from Gill, 2005). We focus on providing examples of environmental effects that are either well documented or, where uncertainty is high, on providing appropriate sources of reference where pertinent. Effects are discussed in the context of a framework that crosses technology types.

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> “RENEWABLE ENERGY DEVELOPERS, REGULATORS, SCIENTISTS, ENGINEERS, AND OCEAN STAKEHOLDERS MUST WORK TOGETHER TO ACHIEVE THE COMMON DUAL OBJECTIVES OF CLEAN RENEWABLE ENERGY AND A HEALTHY MARINE ENVIRONMENT.”

A FRAMEWORK FOR EVALUATING ENVIRONMENTAL EFFECTS

The description of environmental effects of marine renewable energy can benefit from a classification of those effects within a framework. In this paper, we discuss potential impacts cutting across technology types through the construction, operation, and decommissioning stages as well as across spatial and temporal scales. We use a classification and framework modified from that used for wave energy by McMurray (2008) and place the effects of marine renewable energy development in the context of ecological risk assessment by considering stressors and receptors.

- *Stressors* are features of the environment that may change with implementation of renewable energy during installation, operation, or decommissioning of facilities.
- *Receptors* are ecosystem elements with potential for some form of response to the stressor.

The stressors and receptors from that framework applied to wave energy have been modified to account for the broader approach of this synthesis. Our focus is on the unique features of ORED and its interaction with the environment, and, for that reason, we only deal with issues of installation, operation, and decommissioning as they differ from other marine construction projects and activities.

STRESSORS

Scale of Stress

Any stresses related to ORED need to be considered in terms of the stage of development (i.e., survey, construction, operation, and decommission; *sensu* Gill, 2005), and the spatial and temporal extent of the stress, particularly its duration, frequency, and intensity. For any single development, the scale is a potential major factor as small developments may have very localized effects, which consequently may be considered minor or even negligible (such as single devices used in testing). Effects of a large, commercially operating energy development will be at a significantly greater scale (e.g., large wind farm arrays in northern European waters will occupy several hundred square kilometers of the coastal environment). Furthermore, plans for multiple developments in adjacent waters are likely to need an even greater scale of consideration. They will occupy more of the coastal environment, and the survey and construction phase of development will likely extend the duration and frequency of stressors in the vicinity. Hence, the cumulative effect of a number of developments could result in a different set or scale of effects that will ultimately require a different scale or set of management actions (Masden et al., 2010). Given the importance of the spatial and temporal scale in evaluating effects and impacts, we suggest that they form the basis of any consideration of stressors relating to ORED.

When assessing the environmental implications of offshore renewable energy, it is important to follow an appropriate sequence of questioning. Figure 1 outlines such a sequence, which sets out the relationship between the OREDs and the apparent stressors and receptors that have been considered

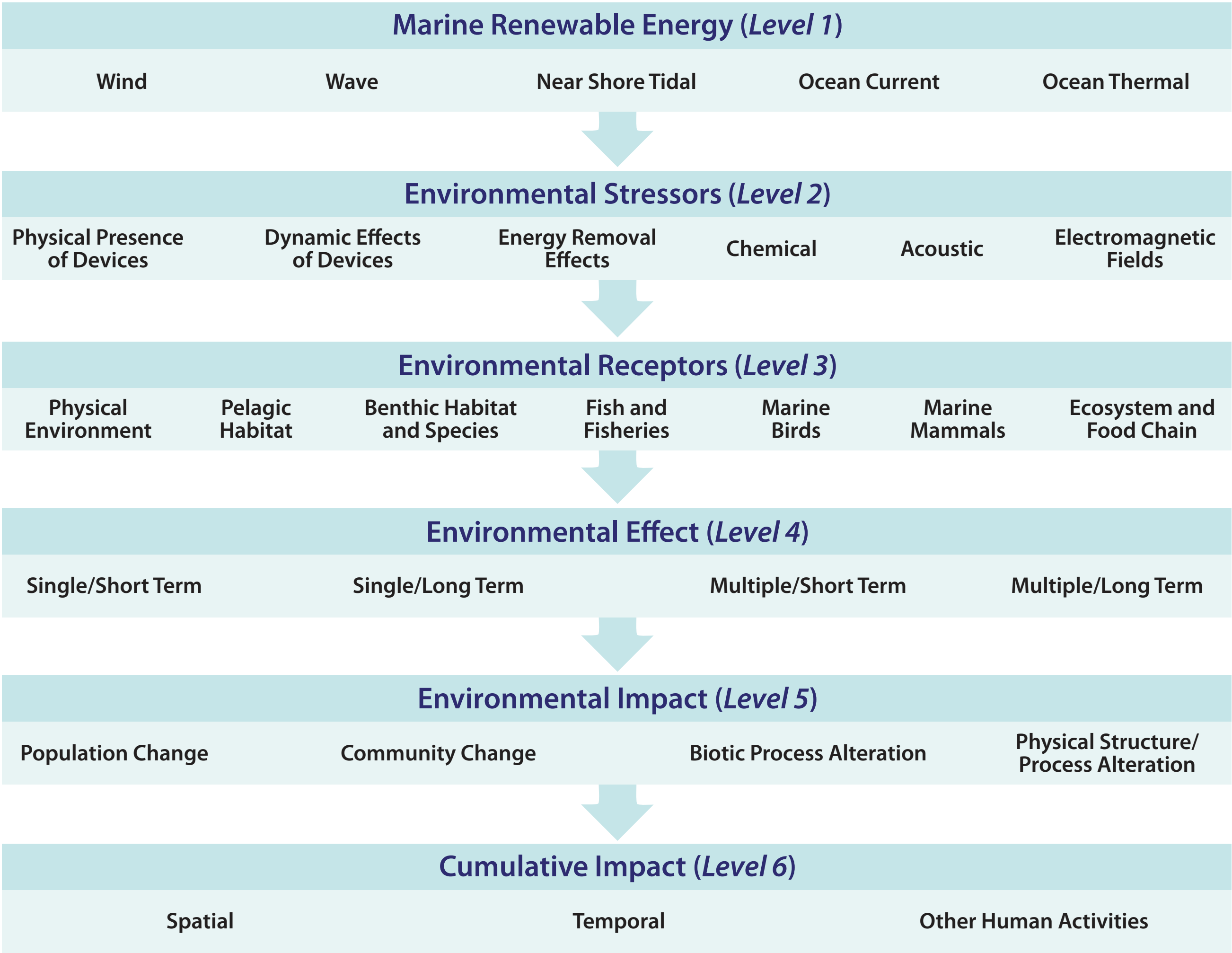

Figure 1. Framework for the consideration of environmental effects of marine renewable energy encompassing different scales. Each ORED will have associated stressors that affect different receptors. Effects vary across scales and receptors; if the effects are sufficient to have impacts, those impacts can apply across different levels from population through biological and physical processes. Cumulative impacts must be considered as an additional dimension to the impacts and should consider stressors from other human impacts.

through studies and the literature. Note that identifying the stressor(s) then leads to a set of receptors that may or may not show the effect(s) of the stress(es). There may be single or multiple stressors and single or multiple receptors; resultant effects may be short term (e.g., during construction or decommissioning) or long term (during the operational phase). This will have consequences for the scale of the effect and any cascading effects that are central to understanding the ecological context.

Effect or Impact?

When discussing stressors in environmental systems, an important semantic distinction should be made between an "effect" of a stressor (Level 4 in Figure 1) on a receptor and an "impact" (Level 5). The two terms are often used interchangeably, but "effect" does not indicate a magnitude or significance, whereas "impact" implicitly deals with severity, intensity, or duration of the effect. Furthermore, impact also deals with direction of effect, which means there can be positive or negative outcomes to the effect of the stressor. The distinction between effect and impact is of crucial importance when considering ORED; a number of studies present findings that suggest or show an effect, but further work is usually required for it to be interpreted as an impact. In terms of Figure 1, the current state of knowledge is at Level 4 rather than Level 5.

In order to move from Level 4 to 5 in Figure 1, there needs to be evidence that the effect of the stressor is significant enough to cause change that will be manifested either within a species' population or community of species. Such impacts can occur either through direct pathways or through more indirect changes to biotic or physical processes. If there are no discernible changes to populations or communities, then it is also necessary to consider whether there may be significant alterations to ecological processes, such as trophic cascade, altered primary production, or nutrient enrichment. Such indirect effects are more difficult to determine but should be considered when determining impacts, particularly over longer periods of time or when cumulative effects of other OREDs are being incorporated (see Figure 1).

Physical Presence of Devices

The mere physical presence of new structures in marine ecosystems results in fundamental changes to the habitat, both above and below the water surface. Above the water surface, seabird and migratory bird impacts are of greatest concern. Marine wind energy devices will have the greatest vertical profile and the most moving parts and potential effects; these effects have been addressed in several studies (Larsen and Guillemette, 2007; MMS 2008). Wave energy devices have differing profiles above water, leading to lower potential for seabird collisions, but this hazard remains to be evaluated.

At the sea surface, some wave devices (e.g., Pelamis, Sea Dragon) may take up significant areas that may need to be considered for migratory surface dwellers in terms of a physical barrier. Furthermore, shoreline and estuarine devices may represent large immovable and impassable objects for migratory species and must be designed appropriately.

Below water, devices will include buoys, rotors or other moving structures (ocean current and tidal), cabling systems, hard-fixed structures (such as monopoles or jackets), rock scour protection, anchors, electrical cables, or pressurized pipes. In the case of land-based ocean thermal energy conversion (OTEC), large pipes will extend along the ocean bottom to significant depths. These new hard surfaces will alter bottom communities; for wave energy in particular, most oscillating devices will be deployed in "featureless" sandy sedimentary habitats. The physical structures will result in settlement habitat for different organisms, creating an artificial reef effect as has been the case for offshore oil and gas platforms and offshore wind farms in Europe (see benthic habitat receptor discussion). In midwater, if no anti-fouling is used, the new structure will provide settlement habitat and likely attract pelagic organisms, the principle that makes "fish aggregation devices" effective (Dempster and Taquet, 2004).

Dynamic Effects of Devices

Moving parts of marine renewable devices can lead to "blade strike," typically viewed as a problem with migratory birds and wind energy devices. In-water turbines, such as current or tidal energy devices, generally move at slower speeds and thus the likelihood of blade strike is lower. However, the speed of the tip of some horizontal axis rotors could be an issue for cetacean, fish, or diving bird strikes (Wilson et al., 2007), and further analysis is merited. An additional consideration is that the energy withdrawn from air, water, or waves may also have potential effects in both near- and far-field scales. Although not generally viewed as an issue by wind energy engineers and scientists, energy removal by devices in water, as well as blockage effects, can lead to localized changes in water movement energy and turbulence—these changes, in turn, can cause benthic sediment scouring and resultant habitat changes. In the water column, modifications to water movement energy and turbulence could lead to changes in turbulence and stratification, potentially altering vertical movements of marine organisms and resulting in prey and predator aggregation.

In the far field, energy reduction could lead to changes in currents and subsequent alterations in sediment transport. Although few studies have been undertaken, surveys at an installed wind farm in the North Sea that used monopole foundations with scour protection showed secondary scouring (Rees et al., 2006). Further, a modeling study based on wind farm data highlighted far-field deposition downstream of the wind turbine foundations (Besio and Losada, 2008). The impact of this effect has not been determined, but if an ORED site is relatively nearshore (e.g., within a few kilometers), beach replenishment and erosion/accretion may be affected, with implications for coastal defense and management. Furthermore, if the site is adjacent to navigation/shipping lanes, then the dredging regime may require alteration. A related effect could be changes to seasonal opening and closing of small estuarine areas, potentially altering the availability of those systems to migratory animals like salmonids (Largier et al., 2008). The existing sediment dynamics and amounts of sediment movement need to be factored into the analysis. These examples demonstrate how the level and scale of effects over time need to be assessed before trying to assign impact.

Removal of sufficient tidal energy could result in changes in tidal range, potentially impacting communities dependent upon periodic exposure; the extreme of this case is seen in the tidal barrage, where blockage of water flow will result in lower water exchange and tidal heights as compared to the natural situation (Goss-Custard et al., 1991). This change in tidal range, in turn, could have impacts on intertidal ecosystems, affecting foraging habitat for shorebirds and distribution of intertidal animals (Goss-Custard et al., 1991). Modeling of turbine-based tidal devices in Puget Sound, Washington, suggests that the proposed amounts of energy reduction will have a relatively minor effect on tidal height (Polagye et al., 2009). Among marine renewable energy devices, those that pressurize water pumped to shore-based turbines may move moderate amounts of water. For OTEC, very large volumes of both cold deep and warm shallow water are moved to take advantage of the thermal difference between them. The potential for impingement and entrainment of mobile species is an issue in this case, analogous to the cooling waters of conventional power plants (Harrison, 1987) or desalination plants; the problem is less severe for the deep cold water intakes due to the lower diversity and biomass of organisms. Warm water intakes may have significant impacts on planktonic and perhaps pelagic organisms (Harrison, 1987), as well as more general effects of OTEC on fisheries (Myers et al., 1986). The response may be expressed ecologically with increased production as a result of more nutrients from the deep water.

> “IT IS CLEAR THAT MUCH WORK IS NEEDED TO ADDRESS THE ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY, AND INDEED TO DEVELOP AN UNDERSTANDING OF POTENTIAL IMPACTS.”

Chemical Effects

In most cases, the effects of chemicals used in marine renewable energy will differ little from other marine construction projects. During deployment, routine servicing, and decommissioning, the expected risks associated with marine vessel operations will be encountered. In normal operations, the potential for spills exists, particularly for those devices that use a hydraulic fluid. Continuous leaching of chemicals may occur if anti-fouling paints are used to minimize biological fouling of devices. As technologies develop, information is needed on the nature of toxic compounds to be used, potential amounts that could be released, responses of receptors, and the fate of the contaminants.

A special case is involved for OTEC, and additional concerns emerge. The working fluid in a closed system (typically proposed to be ammonia, which is highly toxic to fish) could be subject to leaks or spills. The natural chemistry of the deep waters brought to the surface have the potential to alter chemical conditions in the location where water is discharged. Carbon dioxide, for example, could be outgassed to the atmosphere. Higher amounts of nutrients discharged in surface waters could induce algal blooms in areas normally low in surface nutrients (Harrison, 1987). Higher heavy metal concentrations, either from deep natural sources or from heat exchangers, could have toxic effects (Fast et al., 1990). Mitigation for these effects has been suggested (Abbasi and Abbasi, 2000; Pelc and Fujita, 2002). An additional concern could be acidification effects as noted for naturally upwelled waters by Feely et al. (2008).

Acoustic Effects

The ocean is an acoustically diverse environment. From a biological perspective, acoustics are vitally important in animal communication, reproduction, orientation, and prey and predator sensing.

In terms of sounds produced by OREDs, there are a number of potential sources as well as different temporal and spatial scales to consider. It is widely regarded that the construction phase of an ORED will be the most acoustically diverse and the noisiest (Thomsen et al., 2006). There will be a large amount of shipping movements in and out of the area, seismic surveys at the start of the project, and construction noise. If the energy devices require any form of piling, then the predominant noise issue will be associated with pile driving, which is currently of greatest concern for its effects on acoustically sensitive species (Thomsen et al., 2006). Pile driving is associated with monopole wind and tidal turbines and other devices that require small piles for securing jacket foundations. Pile driving can generate very-high-intensity but relatively short-duration noises.

The operational phase of ORED will likely add to the normal background acoustic environment. Devices with subsurface moving parts, such as underwater turbines or hydroplanes, are assumed to be the noisiest; however, data to quantify the noise are lacking. Acoustic profiles from all device types, cables, and other sound-producing components will require measurement to determine the levels and frequencies above background sound.

The main perceived impact of anthropogenic underwater noise is currently focused on fish (Hastings and Popper, 2005) and marine mammals (Southall et al., 2007). Other organisms, such as crustaceans, have not, to our knowledge, been considered in the context of renewable energy devices. However, literature indicates that the crab and lobster larvae are oriented for settling by reef noise (Montgomery et al., 2006). Evidence from Danish studies suggests that marine mammals respond by moving away from an area where construction is taking place (Brandt et al., 2009). Once the noisy activities have ceased, there appears to be no effect, and the mammals occupy the ORED area as much as other adjacent habitats. Hence, there is a definite effect in terms of avoidance, but the effect is not permanent (Brandt et al., 2009). The temporary nature of the avoidance recorded to date is not interpreted as an impact on the marine mammals. With the advent of larger turbines and more extensive arrays of devices, however, the construction period will be extended. Furthermore, in areas such as the strategic development zones in the seas of northern Europe, the cumulative effect of the construction of multiple OREDs is likely to render a large area unfavorable for species that react to the noise through avoidance. Clearly, a better understanding of the transmission of the sounds produced and any threshold intensities (and/or distances from the noise) is required (Thomsen et al., 2006). Whether there is any reaction to sound signals from operational devices has not yet been determined and will inevitably be raised as a question at some point in the future. It is also possible that some animals could be attracted to the produced noise, resulting in other unknown effects like entanglement or area restricted movement. Alternatively, detection of operational noise could lead to avoidance of devices, resulting in fewer interactions. As yet, these are merely points of speculation. It is crucial that these acoustic studies be implemented as rapidly as possible.

Modeling noise in the marine environment is difficult but relatively advanced, certainly in comparison to understanding its effects. Future acoustic modeling of noise should be aimed at understanding the intensity and acoustic profile from a variety of devices such as buoys, turbines, pumps, and cables as they may be useful to assess impacts from various scales of energy facility build-out. Modeling studies of acoustic propagation in ORED areas should also be undertaken to assess the characteristic distances where effects may be located.

Electromagnetic Effects

With the exception of shore-based OTEC or devices that pump pressurized water, marine renewable energy devices by their very nature are required to transmit the electricity produced to shore. This may be accomplished through a network of cables that transmits power from several devices to a large collector cable that is connected to a shoreline substation, or an offshore substation that transforms the energy for the receiving electrical grid system. During transmission of the produced electricity, the cables will emit low-frequency electromagnetic fields (EMFs; Figure 2). At present, the industry standard for design of the cables requires shielding, which restricts the directly emitted electric fields but cannot shield the magnetic component of an EMF. The movement of water and organisms through the emitted magnetic field will then induce localized electric fields (Ohman et al., 2007). If AC cables are used, the magnetic field associated with the cable has a rotational component, which also induces electric fields in the surrounding environment (CMaCS, 2003).

A number of organisms that inhabit the coastal and offshore environment are able to sense either magnetic fields, electric fields, or both. Taxa that have been determined to be magneto-sensitive are generally those that undertake large-scale migrations or use Earth's natural geomagnetic fields for orientation (examples can be found among the cetaceans, herptiles, teleosts, and crustaceans; Kirshvink, 1997). In terms of electroreception, the whole taxonomic class of the Chondrichthyes, the Agnathans, and the Chondrostei have the sensory apparatus to detect and respond to electric fields (Collin and Whitehead, 2004). Such species use electroreception as a fundamental sensory mode to detect the very low-frequency bioelectric fields emitted by prey to locate mates and for orientation. Hence, EMFs emitted by the marine renewable energy harnessing process is most likely to affect animals that use EMFs for spatial location, large-scale movement, small-scale orientation, feeding, or mate finding.

In a review of the state of knowledge, Gill et al. (2005) found that little was known concerning electrically and magnetically sensitive marine animals; for offshore wind farms, there were no studies of direct relevance. However, a small number of studies now exist, some of which relate to just subsea cables (not necessarily from a renewable energy source) and others that have started to address the dearth of information available on the topic.

There is evidence that eels can temporarily respond to EMFs from cables during their migration by diverting from their path of movement (Westerberg and Lagenfelt, 2008). Recent studies conducted in the UK have given initial insight by showing that benthic elasmobranchs can respond to EMFs emitted by subsea cables and also that the cables from an operating wind farm do produce EMFs within the range of intensities previously predicted from models (Gill et al., 2009). EMF responses were variable between individuals, something that is consistent with individual variability within a population, and indicated an attraction to the route of a subsurface

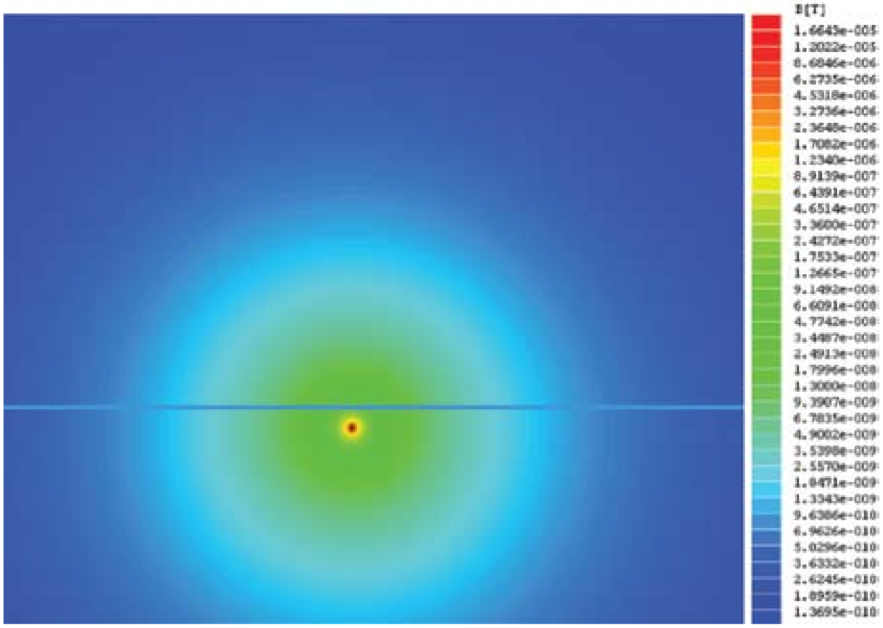

Figure 2. The magnetic field (Tesla) outside an industry standard 13 kV subsea cable buried to 1 m. The seabed surface is shown as the horizontal blue line. *Source: Centre for Intelligent Monitoring Systems, University of Liverpool, UK*

cable when electricity was being transmitted. The few studies to date have highlighted that this is an area of considerable uncertainty, but there appear to be some responses to EMFs emitted by the cables. There are no data available that allow an assessment of impact.

Before-and-after baseline assessment of EMFs associated with cable networks within an array of devices in addition to the main cables to shore is needed. Furthermore, there needs to be a greater research effort to determine the detectability by the potential receptors of a range of fields emitted; the response and potential biological significance of detection, if any, also remains to be determined. At present, major areas of uncertainty exist about the effect of EMFs on receptors.

Thermal aspects of electricity-transmitting cables may also need to be considered. There are predictions that electricity production will increase the temperature in the surrounding sediment and water. A current suggestion is that the thermal effect is a small rise in temperature within a few centimeters of the cable. Whether this small temperature change will represent a stressor to benthic communities is yet to be determined, but will have to be considered in the context of the effect on the benthic community of major disturbance of sediment during cable laying.

RECEPTORS

Physical Environment

With the exception of OTEC, marine renewable energy devices operate by removing kinetic energy from water (or air in the case of offshore wind). For devices at sea or in estuaries, the resultant reduction of energy may lead to downstream effects. Tidal energy devices may result in local acceleration and scouring in some cases, but have the potential to decrease tidal amplitude in downstream areas (the proceedings of a scientific workshop on the environmental effects of tidal energy development held at the University of Washington March 22–24, 2010, will be available at: http://depts.washington.edu/nnmrec/workshop). Shadow effects of wave energy devices may alter sediment transport and deposition as well as have an effect on beach processes (Miller et al., 2007; Largier et al., 2008). Pilot projects across the world to understand and model wave reduction effects are underway. Analysis of project geometry, density, and distance from shore makes modeling feasible to assess effects, but these models have yet to be calibrated in deployments of real devices, particularly at commercial scales.

> “SETTING ENVIRONMENTAL STANDARDS FOR OREDs IS PARTICULARLY URGENT, YET THESE STANDARDS MUST STRIKE AN APPROPRIATE BALANCE.”

OTEC represents a special case because the energy is derived from a thermal difference between cold deep water and warm surface water, most often in the tropics or subtropics. The mixed effluent from these facilities will be released at depths far shallower than where the cold water was taken, resulting in altered thermal regimes (Harrison, 1987).

Pelagic Habitat

The buoys, cables, turbines, spars, and vertical pillars associated with most renewable energy devices will modify pelagic habitats by creating structure where none existed. This will likely have a minimal impact on phytoplankton and most zooplankton, but positive effects on abundance (through aggregation) of other species (e.g., krill, mysids, and fishes). This, in turn, will likely result in attraction of additional predators that might not otherwise aggregate there. This effect is well known in pelagic environments, and, in fact, in certain places, so-called “fish aggregation devices” (FADs) serve an equivalent function to artificial reefs in benthic environments (Addis et al., 2006; Inger et al., 2009; Figure 3). These structures may also serve to facilitate settlement of meroplankton in habitats formerly lacking adequate structure for these species. Impingement, blade strike, collision, and entanglement issues also exist, given the added structural complexity in midwater from many devices. Because of the large water volumes required for OTEC, impingement mortality of planktonic organisms on screens at the plants will likely be a significant problem. In addition, the coldwater effluent, with its higher nutrient level, may stimulate

Figure 3. Tunas and other pelagic species will aggregate around drifting or moored objects as they do around "fish aggregating devices," locally changing the nature of pelagic habitat. *National Oceanic and Atmospheric Administration, Danilo Cedrone (UNFAO)*

Figure 4. Shell mounds accumulate on formerly soft bottoms under oil platforms off California change the nature of the benthic habitat and attract a different community of organisms, including the seastars shown here and fishes (Goddard and Love, 2008). *Donna Schroeder, Minerals Management Service*

blooms, depending upon the depth distribution of the discharge and mixing. Blooms could change the nature of pelagic habitat at selected scales, including water quality and clarity.

Benthic Habitat

Introduction of manmade structures into marine environments may have the greatest impact on benthic habitats and ecosystems, based on structural habitat changes as well as modifications to water circulation and currents. The artificial reef effect will stimulate some species but may negatively affect others (Langhamer and Wilhelmsson, 2009). Placements in sand bottoms will likely result in greater biodiversity (Inger et al., 2009), but this may also affect adjacent benthic communities through greater predation (Langlois et al., 2005). Community growth on buoys (as shown by Langhamer et al., 2009), anchors, and lines may also have effects as these organisms will likely accumulate on the seafloor (e.g., by sloughing off or by routine maintenance of mooring lines and buoy structures; Figure 4). The "shell mounds" evident under long-deployed oil platforms represent an extreme case of benthic habitat modification, but may constitute productive fish habitat (Love et al., 1999; Goddard and Love 2008). Effects on the benthos will likely scale in a nonlinear fashion, affected by connectivity as multiple facilities interact. In the case of new hard bottom over formerly long stretches of sand habitat, for example, these sites have the potential to serve as steppingstones for species, including invasives.

Depending upon the location of discharge and degree of mixing, cold, dense water from OTEC facilities may alter benthic communities as it flows downslope. The large volume of water has the potential to impinge upon benthic environments such as coral reefs, creating thermal stress for the organisms living there (Harrison, 1987). Over the long term, this could lead to changes in the benthic community and, in turn, to structural changes to the habitat.

Fishes

OREDs will affect fish community structure through changes in species composition (Wilhelmsson et al., 2006). As noted above, structures will result in attraction of both pelagic and benthic species. Structures will likely increase the settlement habitat for some species, and diversity and abundance of others in the regions of the renewable energy devices, but it is uncertain to what degree population size will change and thus, whether an impact will occur.

Assuming that there are no avoidance effects of ORED operation (due to noise or EMF) for fished species, it has been suggested that larger-scale OREDs will act as de facto marine reserves due to potential exclusion of fishing within deployment areas (DOE 2009). Thus, they may potentially serve as sources for recruitment to adjacent fished areas. Attraction of large predatory fishes that were absent in the pre-deployment habitat may result in increased mortality of resident species as well as new species attracted to the devices. Fish that migrate through areas where renewable energy devices will be deployed may be affected. In the US Pacific Northwest, for example, juvenile and adult salmon, elasmobranchs, and sturgeon move through regions proposed for wave energy development. As discussed under stressors, behavioral effects resulting from electromagnetic fields, chemical or acoustic signals, or a combination of such stressors could impact movement patterns of these species. Whether there are any interactions between these effects and whether they constitute impacts remain to be evaluated.

Marine Birds and Mammals

This group of receptors is, in general, given the greatest attention in environmental assessments in many countries. For many species, past human activities have led to negative impacts on populations. In addition, they are highly visible, have greater public interest, and are often protected by laws (e.g., the Marine Mammal Protection Act in the United States; International Union for Conservation of Nature [IUCN] classifications; EU Habitat and Species designations). For these reasons, and as species-based conservation management is currently the focus of our activities when considering human impact on the environment, impacts to marine birds and mammals may have greater consequences for the development of marine renewable energy. However, more recent moves toward ecosystem-based coastal management will require greater balance in the considerations of many receptors and the cumulative impacts of ORED on the environment.

There is significant current interest in the potential effects of ORED on seabirds. Lighting and above-water structures may attract seabirds, potentially resulting in collisions, particularly at night when less is known about seabird distribution and behavior. However, evidence to date suggests that birds avoid wind turbine structures and are well able to navigate through the array of turbines (Desholm and Kahlert, 2005). In contrast to onshore windfarms, there are comparatively few records of collision by seabirds with offshore devices. A possible impact may be related to the energy that the birds use in avoiding a wind farm (Masden et al., 2009). When an organism has to significantly alter its path of movement, it expends some energy; how much energy it costs the organism is the effect that needs to be considered. In a recent modeling-based study using data on daily energy demand in several bird species, it was determined that while there is an increase in energy use by large-scale migratory birds on encounter with a single wind farm, they are well able to cope with it. However, the more local, diurnal migratory species have a proportionately greater energetic burden, which may then have impact on the time and energy they have available for acquiring food if the burden is prolonged (Speakman et al., 2009). The cumulative effect of multiple installations therefore requires consideration in the future.

In the ocean, as ORED structures alter habitats, communities, and prey distributions, certain seabirds could have enhanced feeding opportunities and thus aggregate near sites; similarly, changes to beach processes or tidal excursions may affect shorebird foraging. Diving birds may face entanglement, collision, or blade strike with subsurface components or devices. Data gaps to be filled include spatial and temporal abundance of birds, particularly bird activity at night, important areas of bird activity (for example near nesting colonies) that should be avoided, important migration patterns, and potential effects on seabird prey.

As noted above, a diversity of concerns exists for marine mammals across all ORED technologies; entanglement and collision, mainly for cetaceans,

Figure 5. Gray whales (*Eschrichtius robustus*) migrate along the west coast of North America, often within the depth zones where wave energy is proposed for development. The behavioral response of marine mammals to OREDs is an area of high uncertainty. *Craig Hayslip, OSU Marine Mammal Institute*

are primary concerns. Blade strike in the case of ocean current or tidal devices may also be of concern (Wilson et al., 2007). For those devices with cables and moorings, the nature of mooring cables (slack or taut, horizontal or vertical, diameter) is critical to entanglement issues. Should fish and invertebrates be concentrated around devices as predicted, both cetaceans and pinnipeds could be attracted by the feeding opportunity (as has been suggested in studies around Danish wind farms once construction has ceased; DONG Energy et al., 2006), thereby increasing the likelihood of impact. Special attention should be paid to migratory routes or special feeding grounds. In the case of gray whales along the Pacific coast of North America, the migration along the coast passes through optimal regions for wave energy device deployment (Herzing and Mate, 1984; Figure 5). The acoustic signature of the devices could either attract or repel marine mammals. EMF effects on marine mammals is poorly known; for species that rely on Earth's geomagnetic field, there is the potential for orientation to the magnetic fields emitted if they are large enough and/or discernible from background levels, and this should be investigated. Fundamental baseline data will be needed (mammal biology, presence/absence/species diversity, information on prey species) to understand projects' impacts and the cumulative effects as ORED reaches commercial scales. As pilot or demonstration projects are put in the water, immediate monitoring of potential receptor cetaceans and pinnipeds (e.g., videography, beachings, tagging, vessel surveys) will be needed to understand how they interact with OREDs.

CONCLUSIONS

An analysis of published literature demonstrates a dramatic increase in the number of studies dealing with renewable energy; the percentage that deals with environmental effects, however, is relatively meager (Gill, 2005). Throughout this article, we have noted research needs, but they are too numerous to identify in any one place. Instead, Table 1 provides references by technology type that identify needed research; for those documents not widely available, URLs are cited.

It is clear that much work is needed to address the environmental effects of marine renewable energy, and indeed to develop an understanding of potential impacts (Figure 1). Fortunately, OREDs are proceeding somewhat more slowly than terrestrial-based renewables such as wind and solar. In northern Europe, there are a number of operational offshore wind farms. Environmental effects research, however, is increasingly lagging behind the developing technology; there is thus an urgent need for such research (Inger et al., 2009). In the United States and in many other countries, ORED demonstration projects or pilot-scale facilities are under development. Concurrent environmental research at these sites will help reduce uncertainty of effects and identify impacts for all stressor and receptor groups. This research, in turn, will lead to improvements in the best practices for design of devices and arrays and to better performance standards and monitoring requirements for application to commercial-scale development. Setting environmental standards for OREDs is particularly urgent, yet these standards must strike an appropriate balance. If

Table 1. Available literature that provides recommendations for needed environmental research on ocean renewable energy developments (ORED)[1]

ORED Technology	Available References
Offshore Wind	• MMS, 2008 • COWRIE publications (http://www.offshorewind.co.uk/Pages/Publications/Archive) • Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR), 2008 • Wind farms: http://www.ospar.org/documents/dbase/publications/p00385_Wind-farms%20assessment.pdf • Scottish Department for Business Enterprise & Regulatory Reform (BERR), 2008. Reef effects: http://www.berr.gov.uk/files/file43528.pdf • Punt et al., 2009 • OSPAR, 2009. Cables: http://www.ospar.org/documents/dbase/publications/p00437_JAMP%20assessment%20cables.pdf • OSPAR, 2009. Noise: http://www.ospar.org/documents/dbase/publications/p00436_JAMP%20Assessment%20Noise_final.pdf
OTEC	• Harrison, 1987 • Myers et al., 1986
Wave	• Boehlert et al., 2008 (http://hdl.handle.net/1957/9426) • California Energy Commission, 2008. Potential Socio-Economic and Environmental Effects (http://www.energy.ca.gov/2008publications/CEC-500-2008-083/CEC-500-2008-083.PDF) • Inger et al., 2009 • ABP Marine Environmental Research (ABPMer), 2009. Management Strategies: http://www.abpmer.co.uk/files/R1451_Final_05Mar09.pdf
Tidal	• Proceedings of "Environmental Effects of Tidal Energy Development: A Scientific Workshop"[2] (http://depts.washington.edu/nnmrec/workshop) • ABPMer, 2009 (http://www.abpmer.co.uk/files/R1451_Final_05Mar09.pdf)
Ocean Currents	• For the most up-to-date information, see DOE (2009)
Multiple ORED technologies	• DOE, 2009 (http://www1.eere.energy.gov/windandhydro/pdfs/doe_eisa_633b.pdf) • Faber Maunsell and METOC PLC, 2007 (http://www.seaenergyscotland.co.uk) • European Marine Energy Center (EMEC), 2008. Environmental Impact Assessment: http://www.emec.org.uk/pdf/EMEC%20EIA%20Guidelines%20GUIDE003-01-03%2020081106.pdf

[1] Many of these documents are not readily available in the published literature, and we thus provide URLs where they may be found.
[2] The workshop was held March 22–24, 2010; proceedings will be published as a NOAA Technical Memorandum and available from this Web site.

environmental assessments are too lax, we risk severe environmental damage. If the required assessments are overly restrictive, however, there is a risk of inhibiting the development of renewable energy technologies that have the potential to reduce our reliance on fossil fuels.

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