This report summarizes the state of the science of environmental effects of marine renewable energy and serves as an update and a complement to the 2016 Annex IV report, which can be found at http://tethys.pnnl.gov/publications/state-of-the-science-2016.
Marine renewable energy (MRE) is harvested from ocean waves, tides, and currents, as well as ocean temperature and salinity gradients, and from the flow of large rivers (which use technologies similar to those that capture tidal energy). This report focuses on the potential environmental effects from the generation of power from waves using wave energy converters (WECs), tides using tidal turbines, and large rivers using river turbines. Lessons learned from other offshore industries, including offshore wind, oil and gas, and power and communication cables, are included, where appropriate.

A commonly used method of evaluating potential environmental effects from MRE development is the interaction of stressors and receptors. Stressors are those parts of an MRE device or system that may stress or harm the marine environment. Receptors are marine animals, habitats, oceanographic processes, or ecosystem functions that could be harmed by stressors.

mental, 15 counties have collaborated to evaluate the “state of the science” of potential environmental effects of MRE development and to understand how they may affect consenting/permitting (hereafter consenting) of MRE devices.

The information reviewed and synthesized for this report relates to the potential risks that MRE devices pose to marine animals, habitats, and the environment, and may be of value to MRE stakeholders including researchers, regulators, device and project developers, and others. This body of knowledge can inform science-based decision-making for international regulators, and support developers in project siting, engineering design, operational strategies, and monitoring program design. Most particularly, this report should help the research community connect with the latest thinking about MRE interactions, identify scientific collaborators, and assist with adding to the growing body of knowledge. When used in conjunction with site-specific information, this report can help streamline consenting of MRE devices. While most monitoring activity around MRE devices is limited to single devices or very small arrays, much of this research and monitoring will be useful as the industry grows. The information synthesized in the 2020 State of the Science report represents the state of knowledge derived from studies and monitoring, built on publicly available peer-reviewed scientific literature and reports published by researchers, developers, and government agencies, seen through the lens of many of the best researchers in the field. The analyses and conclusions drawn in this report are not meant to take the place of site-specific analyses or studies used to make project siting decisions or to direct consenting actions.
As the MRE industry advances, the body of knowledge surrounding potential environmental effects of MRE development will continue to grow, informing our perception of risk. It is possible that as additional data are collected, we may retire or set a lower priority for certain risks. The evidence base for risk retirement will be informed by our growing knowledge about the nature of specific stressor-receptor interactions, helping to determine which interactions have sufficient evidence to retire those risks, and where significant uncertainties remain. However, risk to marine animals, habitats, and the environment may continue to present challenges to consenting commercial-scale development.

**SUMMARY OF POTENTIAL ENVIRONMENTAL INTERACTIONS ASSOCIATED WITH THE DEVELOPMENT OF MARINE RENEWABLE ENERGY DEVICES**

MRE is an emerging industry that has had a limited number of small deployments and no full-scale commercial deployments to date. As a result, the paucity of baseline and post-installation data continues to drive a level of uncertainty among regulators and stakeholders that increases the perception of risk for many potential interactions between MRE devices and marine animals, habitats, and the environment. This lack of data continues to confound our ability to differentiate between actual and perceived risks. Ultimately, the risk to marine animals, habitats, and the environment is a function of the attributes of the MRE device (static or dynamic), type of device (wave, tidal, or riverine), and the spatial scale of a particular installation (single device or array). Risk is defined as the interaction of the probability or likelihood of a deleterious outcome, with the consequences, if such an outcome occurs.
BENEFITS OF MARINE RENEWABLE ENERGY
The acceleration of MRE research and development around the world contributes to locally-derived secure energy sources that have the potential to create significant benefits, including positive impacts on local communities, local infrastructure and services, local employment and businesses, and the export of products and services. In addition, MRE development has the potential to combat the effects of climate change, including ocean acidification and increasing ocean temperatures. Deleterious effects of climate change are already affecting many marine and coastal resources, and will continue to affect marine animals and habitats as well as eroding beneficial human uses from the harvest and aquaculture of seafood organisms, coastal protection from storms and erosion of shorelines.
COLLISION RISK FOR ANIMALS AROUND TURBINES

Tidal and river energy devices may pose a risk of collision to marine mammals, fish, and diving seabirds. To date, there have been no observations of a marine mammal or seabird colliding with a turbine, and the limited number of interactions of fish in close proximity to a turbine have not resulted in obvious harm to the fish. It is expected that collisions, if they occur, will be very rare events that will be difficult to observe in the fast-moving often murky waters. In addition, the likely consequences of a collision are not known, with outcomes ranging from injuries from which the animal may recover to the death of the animal. There is limited evidence and understanding of how marine animals behave in the presence of underwater structures; it is difficult to determine how well marine mammals, fish, and seabirds may be able to sense, react to, and avoid an operating turbine. In the absence of this behavioral information, most progress in understanding collision risk focuses on understanding the presence of marine animals of interest in the vicinity of turbines, supported by computer modeling that simulates potential collisions.

RISK TO MARINE ANIMALS FROM UNDERWATER NOISE GENERATED BY MARINE RENEWABLE ENERGY DEVICES

Marine animals use sound in the ocean like terrestrial animals and humans use sight on land—to communicate, navigate, find food, socialize, and evade predators. Anthropogenic noise in the marine environment has the potential to interfere with these activities.

Progress on quantifying the direct and indirect effects of underwater noise on marine animals has been complicated by the relatively small number of MRE devices that have been deployed. Difficulties in accurately measuring noise from MRE devices and the challenge of understanding how underwater noise affects the behavior of marine animals, confound our understanding. However, international technical specifications provide a standardized approach for measuring noise from MRE devices. The underwater noise from several MRE devices has been measured using this specification and found to fall below regulatory action levels and guidance developed in the United States for protecting marine mammals and fish from harm due to underwater noise.

Evidence suggests that underwater noise emitted from operational MRE devices is unlikely to significantly alter behavior or cause physical harm to marine animals.
RISK TO ANIMALS FROM ELECTROMAGNETIC FIELDS EMITTED BY ELECTRIC CABLES AND MARINE RENEWABLE ENERGY DEVICES

Electromagnetic fields (EMFs) occur naturally in the marine environment, while anthropogenic activities may alter or increase EMF, including those from MRE export cables. Cables are commonly buried, laid on the seafloor, or draped in the water column between devices. EMF emissions are evaluated by measuring the magnetic and induced electrical fields from cables and devices. Not all marine animals are able to detect EMFs; only a few species have the sensory capabilities to sense and react to these stimuli. The animals most likely to encounter and be affected by EMFs from MRE systems are those that spend time close to a power cable over extended periods of time – most commonly sedentary benthic organisms. EMFs are thought to cause changes in behavior and movement of susceptible animals, and potentially long-term changes in growth or reproductive success.

The evidence base to date suggests that the ecological impacts of EMFs emitted from power cables from single MRE devices or small arrays are likely to be limited, and marine animals living in the vicinity of MRE devices and export cables are not likely to be harmed by emitted EMFs.
CHANGES IN BENTHIC AND PELAGIC HABITATS CAUSED BY MARINE RENEWABLE ENERGY DEVICES

The effects of MRE installations on benthic and pelagic habitats are very similar to those seen for offshore wind, oil and gas exploration and production, the presence of navigation buoys, and installation of power and communication cables. The deployment of MRE devices requires the installation of gravity foundations, pilings, or anchors that may alter benthic habitats, as well as mooring lines, transmission cables, and mechanical moving parts in the water column that may affect pelagic habitats. These structures on the seafloor or in the water column may change the presence or behavior of animals, and may act as artificial reefs. Installation of export power cables can disturb and change habitats over a long thin area. Scouring of sediments around anchors and foundations may also alter benthic habitats.

MRE systems may provide habitat for biofouling organisms, as well as attracting fish and other animals, creating *de facto* artificial reefs and marine protected areas. The attraction of fish may boost fish populations in nearby areas as well. Overall, changes in habitat caused by MRE devices and arrays are likely to pose a low risk to animals and habitats if projects are sited to avoid rare or fragile habitats.
CHANGES IN OCEANOGRAPHIC SYSTEMS ASSOCIATED WITH MARINE RENEWABLE ENERGY DEVICES

The movement of ocean water defines the physical and biological systems within which marine organisms and habitats exist. The deployment of MRE devices has the potential to affect oceanographic systems, causing changes in water circulation, wave heights, and current speeds, which in turn can affect sediment transport and water quality, within both nearfield and farfield environments around MRE devices. While a small number of MRE devices will not result in changes that are measurable relative to the natural variability of the system, larger-scale array deployments may have the potential to disrupt natural processes.

Evidence of potential changes to oceanographic systems comes largely from numerical models, with a small number of laboratory flume studies and field programs. Field data are needed to validate the numerical models as larger commercial arrays are deployed. For small numbers of MRE devices, this risk is very low.

ENCOUNTERS OF MARINE ANIMALS WITH MARINE RENEWABLE ENERGY DEVICE MOORING SYSTEMS AND SUBSEA CABLES

Most WECs and floating tidal turbines must be anchored to the seafloor, using mooring lines to maintain their position within the water column or on the water surface. MRE arrays may include transmission cables for device interconnection or to connect to offshore substations. The mooring lines and cables associated with MRE device mooring systems have the potential to entangle or entrap large marine animals. The species considered to be at risk of encounters with MRE mooring systems and subsea cables are large migratory baleen whales. These concerns are raised because of the entanglement of marine mammals with fishing gear and lines. However, MRE cables and lines do not have loose ends or sufficient slack to create an entangling loop, as does fishing gear. This risk is considered to be very low.
SOCIAL AND ECONOMIC DATA COLLECTION FOR MARINE RENEWABLE ENERGY

The potential social and economic impacts of MRE development (including impacts on communities, employment, infrastructure and services, and regional commerce) must be considered during consenting processes and for strategic planning purposes. In addition, it would be helpful for government oversight and for MRE project developers to follow trends in social and economic data to understand whether the promise of improvements to local communities and minimal effects are realized.

The responsibility for collecting social and economic data for consenting purposes and to follow long term trends should be divided between MRE developers collecting site-specific data, and governments taking responsibility for larger regions and strategic level analyses.

ENVIRONMENTAL MONITORING TECHNOLOGIES AND TECHNIQUES FOR DETECTING THE INTERACTIONS OF MARINE ANIMALS WITH TURBINES

The interaction of marine animals with tidal and river turbines remains the least understood aspect of potential MRE effects and has been hampered by the inability to observe these interactions. These challenges require the design of monitoring equipment that can survive in harsh marine environments, and the ability to manage power to operate instruments and onboard data acquisition systems.

The most common instruments used to observe interactions of marine animals with MRE devices are passive and active acoustic instruments and optical cameras. Passive acoustic monitoring uses hydrophones measure underwater sound including vocalizing marine mammals. Active acoustic systems generate sound and record the return signal to visualize objects and to develop high-resolution imagery of underwater environments as well as quantify fish abundance and distribution. Optical cameras are used to monitor the distribution of marine animals in the vicinity of an MRE device and to determine species, individual animal size, and abundance. Groups of sensors can be integrated into monitoring platforms, which may be deployed autonomously, relying on battery power, or cabled to the shore for power and data transfer.
MARINE SPATIAL PLANNING AND MARINE RENEWABLE ENERGY

The growth of MRE will result in the increasing use of marine space and the potential for conflict with existing ocean uses, which can be partially addressed through implementation of marine spatial planning (MSP). MSP seeks to manage competing marine uses while balancing environmental, social, and economic interests to support sustainable development of the oceans. MSP has the potential to increase transparency and certainty for industry, improve environmental protection, reduce sectoral conflicts, and provide opportunities for synergies.

The 15 nations of the OES-Environmental initiative were surveyed about their MSP practices in relation to MRE development. Their practices varied widely from intentional inclusion of MRE in MSP processes, to application of MSP principles without a formal MSP plan, to the lack of MSP used in MRE development.
Adaptive management (AM) has the potential to support the sustainable development of the MRE industry by enabling projects to be deployed incrementally in the face of uncertainty about potential effects, and to assist in closing knowledge gaps through rigorous monitoring and review. AM is an iterative process, also referred to as “learning by doing,” that seeks to reduce scientific uncertainty and improve management through periodic review of decisions in response to the knowledge gained from monitoring.

AM has been used to guide the implementation of MRE monitoring programs and has successfully allowed a number of projects worldwide to progress. If information from routine monitoring shows that the level of an effect is likely to cause an unacceptable impact, corrective actions can be taken. Conversely, if monitoring information indicates that risks have been overestimated, monitoring and mitigation requirements may be reduced.

**Risk retirement** is a process for facilitating the consenting of small numbers of MRE devices, whereby each potential risk need not be fully investigated for every project. Rather, MRE developers can rely on what is known from already-consented projects, from related research studies, or from findings from analogous offshore industries.
RISK RETIREMENT AND DATA TRANSFERABILITY FOR MARINE RENEWABLE ENERGY

Risk retirement does not take the place of any existing regulatory processes, nor does it replace the need for all data collection before or after MRE device deployment. Regulators may request additional data collection to verify risk retirement findings and to add to the growing knowledge base.

By cautiously applying existing learning, analyses, and monitoring, data sets from one country to another, among projects, and across jurisdictional boundaries, regulators may be able to make monitoring requirements less stringent, reducing costs to the MRE industry over time.

As a means of facilitating the consenting of a small number of MRE devices, a risk retirement pathway has been developed to evaluate the potential risks of specific stressor–receptor interactions. Preliminary evidence indicate that the risk of underwater noise and EMF from small numbers of MRE devices could be retired. As larger MRE arrays are developed, these stressors may need to be reassessed.

PATH FORWARD FOR MARINE ENERGY MONITORING AND RESEARCH

In the four years since the publication of the 2016 State of the Science report, our understanding of several stressor–receptor interactions has increased as a result of additional MRE deployments and monitoring efforts, research studies in the laboratory and in the field, and modeling studies. Substantial uncertainties still remain that require ongoing research and monitoring, particularly for collision of animals with turbines and for effects of future large arrays.

The body of knowledge about potential effects of MRE development can be used to help streamline consenting processes and support the responsible development of MRE through the implementation of strategies such as marine spatial planning, adaptive management, and risk retirement. How these management strategies may support consenting and management of MRE project needs to be considered through these lenses:

- Data collection, analysis, and reporting for consenting must be proportionate to the size of the MRE project and the likely risk to marine animals and habitats.
- Both MSP and AM can play critical roles in assessing whether sufficient evidence has been gathered to evaluate potential risks of MRE development to the marine environment.
- Knowledge gained from consented MRE deployments, along with lessons learned from analogous offshore industries and research projects, can be evaluated to determine their applicability to inform consenting at new MRE sites. Data transferability, within the risk retirement pathway, can make the routine transfer of evidence more efficient.
- A fully data-supported risk retirement process can help determine which interactions have sufficient evidence and where significant uncertainties remain. By retiring specific issues for a small number of MRE devices, resources can be directed towards examining the most challenging stressor–receptor relationships.
REPORT AND MORE INFORMATION

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Go to https://tethys.pnl.gov for a robust collection of papers, reports, archived presentations, and other media about environmental effects of MRE development.