11.0 Summary and Path Forward

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The 2024 State of the Science report has brought together the most up-to-date information on potential environmental effects of marine renewable energy (MRE) development on marine animals, habitats, and ecosystem processes, as well as social and economic systems, using information that is publicly available as well as expert input. The report has been reviewed by over 56 experts. The reviewers provided in excess of one thousand comments during the drafting of the report that have been addressed in this version. The OES-Environmental country representatives from the 16 participating countries helped to scope the entirety of the report and provided valuable contributions to all chapters. The input from these contributors and reviewers has resulted in the most complete compendium of research and monitoring findings possible. While there is new and exciting research underway that should further illuminate the risks of MRE stressor-receptor interactions in the near future, suppositions and incomplete results from unpublished studies were not included in order to maintain the integrity, and decrease the uncertainty, of the messages in this report.

The *2024 State of the Science* report encompasses an introduction and a look ahead (this chapter), as well as nine chapters that provide details of research and monitoring findings around the world, identify gaps in knowledge, and list recommendations for addressing these gaps (Table 11.1). The main messages from each chapter are briefly summarized below, followed by the outlook for OES-Environmental collaborations over the coming years.

11.1. SUMMARY OF FINDINGS

The introductory chapter provides background on the benefits of MRE, the importance of measuring environmental interactions for all deployed devices, and the stressor-receptor framework. Chapter 1 also summarizes the work of OES-Environmental and introduces ocean thermal energy conversion (OTEC) as an MRE source that has not been addressed in previous OES-Environmental work.

11.1.1. POTENTIAL ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY PROJECTS AROUND THE WORLD

Chapter 2 examines the status of environmental monitoring around deployed and upcoming MRE devices in countries around the world, with a major emphasis on OES-Environmental member countries. While there is currently no accurate count of the number of MRE devices that have been deployed around the world over the past two decades, it is safe to say that many have had no environmental assessments or post-installation monitoring associated with them. However, 86 MRE projects were identified for which environmental baseline and/or post-installation monitoring were carried out, with an emphasis on stressor-receptor interactions. The United Kingdom, Europe, and the Americas lead with the greatest number of MRE devices with associated environmental monitoring, while other locations around the world are also moving forward with environmental assessments and research. The presence of established test centers appears to have a strong influence on the number of deployments with associated environmental monitoring, and likely also on the number of overall deployments. Other factors that encourage the number of deployments with environmental data collection include the available resources in a country, including the presence of research institutions and researchers; a developed regulatory process for consenting; a developed supply chain; offshore expertise; and other maritime uses in the vicinity. Five case studies were used to highlight the different types of monitoring that have been required for tidal, riverine, and wave energy deployments, as well as differences that exist among jurisdictions. Recommendations for improved outcomes for all MRE projects include: the need to collect baseline data before deployment, relying on existing data where available; early identification of likely risks that drive consenting, as well as gaps in data and analyses to understand those risks; a push to collaborate with researchers, communities, and other developers for optimal outcomes; and a plea for transparency in data accessibility to move the entire industry forward.

Table 11.1. Chapters in the Ocean Energy Systems-Environmental *2024 State of the Science* report

Chapter	Chapter Title
1	Marine Renewable Energy and Ocean Energy Systems-Environmental
2	Progress in Understanding Environmental Effects of Marine Renewable Energy
3	Marine Renewable Energy: Stressor-Receptor Interactions
4	Social and Economic Effects of Marine Renewable Energy
5	Stakeholder Engagement for Marine Renewable Energy
6	Strategies to Aid Consenting Processes for Marine Renewable Energy
7	Education and Outreach Around Environmental Effects of Marine Renewable Energy
8	Marine Renewable Energy Data and Information Systems
9	Beyond Single Marine Renewable Energy Devices: A System-Wide Effects Approach
10	Environmental Effects of Marine Renewable Energy in Tropical and Subtropical Ecosystems
11	Summary and Path Forward

11.1.2. MARINE RENEWABLE ENERGY: STRESSOR-RECEPTOR INTERACTIONS

Chapter 3 encompasses the progress made on understanding the major stressor-receptor interactions that help delineate potential risks from MRE development. Each interaction has been the focus of multiple research and monitoring studies since the *2020 State of the Science* report.

COLLISION RISK FOR MARINE ANIMALS AROUND TURBINES

Uncertainty around collision risk of marine animals with turbine blades continues to be a key barrier to consenting new tidal and riverine energy projects. The steps that could result in a marine animal colliding with a rotating turbine blade have been parsed into a series of actions that must take place sequentially. There are differing terminologies and thoughts on each step, but generally the animal must be in the vicinity of a turbine for a potential encounter to occur, and determine whether to avoid the turbine by swimming in the opposite direction, above, below, or around the turbine. If the animal progresses closer to the turbine, there is still an opportunity for it to evade, or take last minute action, to move away from the rotating blades. If these actions fail, a collision may occur. Additional research studies have added evidence to the likelihood that marine mammals may detect the turbine, and avoid the rotor swept areas when the tidal currents increase and the blades begin to rotate. Increasing use of underwater video to examine marine animal interactions with turbines is adding to our understanding of the risk of collision. Research has shown that adult salmon in a river are not likely to be close enough to rotating riverine turbine blades to collide. However, salmon smolts are more likely to pass through the rotor swept area and become disoriented, although longer-lasting harm has not been shown. Diving seabirds have not been observed near rotating turbines but appear to gather in areas where turbines might be installed. The accuracy and validation of numerical models simulating collisions have improved, particularly with the addition of agent-based models that depict single fish, as well as the more traditional collision risk and encounter risk models that examine marine mammals and fish. The low number of deployments and the challenges of collecting nearfield data limit our understanding of collision risk. There is a need for additional data collection and research studies before collision risk can be considered for retirement.

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

The potential risk to marine animal behavior from underwater noise continues to be of concern to stakeholders and regulators for both turbines and wave energy converters (WECs). Measurements of acoustic output from MRE devices have become an important aspect of monitoring around deployed devices. The international specification developed by the International Electrotechnical Commission Technical Committee 114 (TC114) provides guidance on how to accurately measure noise from an MRE device; the specification has been tested and appears to be headed toward adoption as a standard, following updates. This will provide much needed comparability among underwater noise measurements. Coupled with the US standards and guidance for levels of underwater noise that will disturb or harm marine mammals and fish, the outcome of monitoring to date from turbines and WECs suggests that the operational noise is not likely to be harmful for marine species, at least for small numbers of devices. New frameworks for examining and measuring underwater noise, and new modeling approaches provide further confidence that this stressor is unlikely to be a significant risk for marine animals, for small developments. This risk is considered to be retired for small numbers of devices.

ELECTROMAGNETIC FIELD EFFECTS FROM POWER CABLES AND MARINE RENEWABLE ENERGY DEVICES

There have been relatively few field studies of potential electromagnetic field (EMF) effects on marine animals in the past four years, although new methods for detection in the field and laboratory studies have continued. Laboratory studies have challenged many EMF-sensitive marine species with levels of EMFs that are higher than those found from MRE export cables. The marine animals most likely to be susceptible to EMF effects, including certain species of sharks, rays, skates, as well as benthic crustaceans like crab and lobster, have been the focus of most investigations. While the specific biology, physiology, and life stage of many species may show differing levels of sensitivity, for the level of power carried by export cables from MRE devices, the EMFs signatures are generally believed to be below a significant risk level. This has led to the understanding that this risk is considered to be retired for small numbers of devices.

CHANGES IN BENTHIC AND PELAGIC HABITATS CAUSED BY MARINE RENEWABLE ENERGY DEVICES

Changes in benthic and pelagic habitats are inevitable with any development in the marine environment. However, the small footprint of MRE anchors, foundations, mooring lines, cables, and surface floats from small numbers of devices are not likely to cause significant harm to the marine environment, provided they are sited carefully. Many studies related to changes in habitats have been undertaken in the past four years, including those focusing on understanding marine animal distributions and habitat use pre- and post-installation of MRE devices, as well as characterizing the composition of biofouling and artificial reef assemblages. The lack of evidence of harm to benthic and pelagic habitats has led the risk from this stressor-receptor interaction to be considered as retired for small number of devices.

CHANGES IN OCEANOGRAPHIC SYSTEMS ASSOCIATED WITH MARINE RENEWABLE ENERGY DEVICES

Changes in wave heights, water circulation, and water column stability as a result of the operation of MRE devices continue to be investigated using numerical models, with some attempts to validate the models with field data collection. These field studies have not yielded results because the changes that could be attributed to small numbers of MRE devices appear to be less than the natural variability of the system. Until large arrays are deployed, it is likely that numerical models will continue to provide the best insights into potential risks to oceanographic systems. For small numbers of devices, the risk is considered to be retired.

With OTEC under consideration for tropical waters, the risk from the discharge of large volumes of cold water to the upper water column and the marine animals and plants that live there must be considered. With few operational OTEC plants in the world, there is limited evidence of the magnitude of the risk. The risk will be mitigated by designing the cold water discharge to place the return water below the thermocline for all OTEC developments.

ENTANGLEMENT RISK WITH MARINE RENEWABLE ENERGY MOORING LINES AND UNDERWATER CABLES

The risk of large marine animals becoming entangled among mooring lines or draped cables between MRE devices remains theoretical. There is no evidence to date that entanglement will occur; however, stakeholder concerns remain. The advent of floating offshore wind platforms has raised this issue in recent years. While nothing definitive can be said about this risk, for small numbers of MRE devices, it should be considered not to be significant. As larger arrays are deployed, monitoring results from floating offshore wind farms and MRE arrays may provide further insight into the potential risk. This chapter summarizes what little can be determined from available information.

DISPLACEMENT OF ANIMALS FROM MARINE RENEWABLE ENERGY DEVELOPMENT

Once larger MRE arrays are deployed, migratory marine species and those that move across short distances in the water column or on the seafloor may have their normal movement patterns disrupted by the presence and operation of the devices. Displacement is defined as the outcome of attraction, avoidance, or exclusion that may be triggered by animal responses to one or more stressors, with potential consequences at the individual to the population levels. This risk is considered to be low at this time, with models used to determine the likely risk dependent on location and populations, however little data to inform this risk will be gathered until larger arrays are deployed. This chapter lays out a framework and recommendations for addressing displacement as the MRE industry grows, including knowledge gaps that remain to be filled.

11.1.3. SOCIAL AND ECONOMIC EFFECTS OF MARINE RENEWABLE ENERGY

Social and economic effects of MRE development and operation have not received a great deal of research focus. While aspects of social and economic effects and benefits are considered as inputs for consenting permission, data are often lacking or not fit for purpose for the location, scale, or communities involved. Chapter 4 examines what is known about social and economic effects as they pertain to MRE development, highlighting potential interactions with various groups such as fishers, maritime industries including the supply chain and workforce, coastal communities, Indigenous people, conservation, tourism, and energy end-users. While conclusions about social and economic effects are highly site-specific, there are common types of information that ought to be collected, as recommended in this chapter.

11.1.4. STAKEHOLDER ENGAGEMENT FOR MARINE RENEWABLE ENERGY

Engaging stakeholders leading up to the development of an MRE project has been shown to be linked to an increased chance that the project will proceed with minimal opposition. Chapter 5 discusses the range of stakeholder involvement that begins with legally mandated informing and involving of stakeholders, through preferred practices that bring stakeholders further into the process for siting and designing MRE projects. This increased level of engagement can provide a greater sense of stewardship for MRE projects, as well as engage local communities and those with skills and knowledge that can benefit the project. Implementing best practices and measuring their outcome are key parts of stakeholder engagement processes that have shown levels of success in other industries, as described in this chapter.

11.1.5. STRATEGIES TO AID CONSENTING PROCESSES FOR MARINE RENEWABLE ENERGY

Over the past four years, OES-Environmental has focused on presenting the science behind what is known about the potential risks of MRE development on marine animals, habitats, and ecosystem processes, in formats and methodologies that are accessible and applicable to consenting processes, across the OES-Environmental countries. Chapter 6 documents the work and describes the use of the various tools that have been developed by OES-Environmental and other groups. The overall risk retirement process has been expanded to include the concept of data transferability, whereby datasets collected and analyzed for MRE deployments in one locale can be made available and relevant to new projects with similar attributes. In addition, the process of retiring risks for certain small MRE developments has been evaluated across several stressors, using evidence bases of seminal papers and reports, and tested at a series of expert workshops. This process resulted in consensus around retiring risks for four stressor-receptor interactions for small numbers of MRE devices: underwater noise, EMFs, changes in habitats, and changes in oceanographic systems. There is not sufficient evidence to retire the risk of collision, while displacement and entanglement risks have not yet been evaluated.

The results of the risk retirement and data transferability processes were made more accessible to consenting processes by equating the stressor-receptor interactions with the appropriate category of environmental regulation. The major categories of environmental regulation found across OES-Environmental countries include those that address: protection of species and populations; protection of habitats; protection of water quality; and support for social and economic well-being. A series of guidance documents have been written that provide access to the science that supports understanding the potential risk of MRE development on the marine environment. The guidance documents can provide a starting point for discussions around consenting between developers and regulators.

Other strategies and tools that can be used to assist with regulatory processes have also been reviewed, including adaptive management, marine spatial planning, and a series of tools specific to individual countries. The chapter includes case studies that have successfully applied these strategies and tools for MRE development.

11.1.6. EDUCATION AND OUTREACH AROUND ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY

Chapter 7 addresses the efforts and the need for education and outreach to a variety of audiences, to ensure that the benefits, challenges, and opportunities of developing MRE are well disseminated among the wide range of stakeholders who make up the MRE community and beyond. The process of developing and disseminating education and outreach materials entails tailoring the appropriate messages for a variety of audiences. In order to engage and educate these groups, OES-Environmental has developed coloring pages for young children, more complex and hands-on materials for school-age children, academic content for high school and university students, and straightforward but sophisticated messaging for the public. Vehicles such as fact sheets (available in print and online), podcasts, videos depicting potential environmental effects of MRE devices, presentations at conferences, social media posts, and one-on-one interactions with the range of students, researchers, MRE developers, regulators and advisors, and local communities, help to spread the word about the value of MRE. As this chapter describes, a more aware public is more likely to support and advocate for a renewable energy technology they understand, such as MRE.

A series of examples of MRE-focused outreach and education programs are presented as good practices, and examples of MRE-focused education programs from many OES-Environmental countries are described.

11.1.7. MARINE RENEWABLE ENERGY DATA AND INFORMATION SYSTEMS

As the MRE industry grows, increasingly large amounts of data and information are being generated from device testing, environmental monitoring, numerical modeling studies, laboratory experiments, and more. These data and information are essential to supporting MRE progress, including the need to share successes and failures, ensuring that hard fought lessons are not lost and that results of studies are available to be built upon and not repeated. The United States has created the Portal and Repository for Information on Marine Renewable Energy (PRIMRE) a comprehensive data and information system that is headlined by Tethys, the system that supports inquiries into potential environmental effects of MRE, and acts as the platform that supports all OES-Environmental activities. Tethys and analogous systems from other countries that curate, store, and disseminate information on environmental effects of MRE are described in Chapter 8.

11.1.8. BEYOND SINGLE MARINE RENEWABLE ENERGY DEVICES — A SYSTEM-WIDE EFFECTS APPROACH

The MRE industry is moving from deploying single devices and demonstration projects toward multiple devices, while planning for large-scale commercial arrays to meet end-user needs for power. As the industry scales up, there is a need to understand what potential effects larger deployments might have on marine animals, habitats, or ecosystem processes. However, almost all the knowledge about environmental effects to date has been gleaned from single devices or small arrays (up to six devices). Chapter 9 looks at strategies for increasing this knowledge from single devices to arrays, determining that different stressor-receptor interactions are likely to scale in different ways. In addition, ecosystem models that simulate changes to marine trophic networks from natural and anthropogenic factors have not taken into account potential effects of MRE development; changes to the most common ecosystem models that account for other uses such as fisheries, are suggested in order to include effects of MRE. Finally, this chapter examines cumulative effects of MRE development on the marine environment, in conjunction with other anthropogenic uses of the ocean, and provides strategies for examining these effects in a holistic approach.

11.1.9. POTENTIAL ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY IN TROPICAL AND SUBTROPICAL ECOSYSTEMS

So much of the knowledge that has been gained concerning potential environmental effects of MRE development comes from temperate regions. With more and more countries entering into the MRE space, there are increasing numbers of MRE developments within tropical and subtropical regions. The mix of MRE technologies that are more likely to be deployed in these regions will differ somewhat from those in temperate regions, with greater contributions from OTEC, perhaps salinity gradients, and wave energy devices. Tropical and subtropical ecosystems also differ significantly from their temperate counterparts, with higher biodiversity and more complex food webs. Chapter 10 examines these differences and recommends monitoring and research approaches that are better suited to tropical and subtropical ecosystems. In general, these ecosystems can best be approached as complex entities, rather than parsed into separate stressor-receptor interactions as has been done for temperate ecosystems. However, many of the same interactions will be applicable to tropical and subtropical ecosystems, allowing for considerable knowledge transfer from OES-Environmental's and others' existing research.

11.2. PATH FORWARD

As the fourth phase of OES-Environmental draws to a close, there remain substantial areas of uncertainty about MRE environmental effects, even as new fields of inquiry become important. The body of knowledge that has been gleaned over the past 14 years (2010-2024) represents a level of understanding that can be used to facilitate consenting of single devices and small arrays, as well as provide insight on how larger arrays might fit into the receiving environment. With the new phase (Phase 5) of OES-Environmental, the country representatives recognize the value of four new areas of work that will provide actionable advice and reduce uncertainty for MRE effects. Those four new areas encompass the ability to use the compendium of knowledge acquired to date to advise on environmental acceptability; to examine potential environmental effects of off-grid MRE applications; and to delve further into potential system-wide effects of MRE as the industry scales up. In addition, there is a need to further pursue tools and outcomes of potential social and economic effects of MRE. Each of these areas of focus for Phase 5 of OES-Environmental is described in more detail below.

11.2.1. ENVIRONMENTAL ACCEPTABILITY

Much like other important processes that are needed for the MRE industry to succeed, environmental acceptability is essential (Hodges et al. 2023). Science-directed guidance will be created for MRE developers that draws on the past 14 years of OES-Environmental research. This guidance will be designed to ensure that MRE devices minimize harm to the environment. The knowledge gained from examining stressor-receptor interactions for small numbers of devices (1-6), and for increasingly larger scale arrays, will guide the development of advice on the design, deployment, operation, maintenance, and decommissioning of MRE devices. Each major archetype of WEC, turbine, and other MRE devices will be examined to parse the risks that each might cause, by stressor-receptor interaction, and advice tailored accordingly. By considering the intersection of MRE device types across diverse ocean environments and market applications, a matrix of guidance will be provided to developers for forward-looking design and operation. This same information will be available to regulators and stakeholders so that they will gain confidence in applying data from already-consented MRE projects, research studies, and appropriate surrogates for consenting new MRE projects as well as for designing post-installation monitoring programs. As a part of this work, marine net gain (i.e., generating positive impacts from activities) and its application to MRE will be assessed across the OES-Environmental countries (Hooper et al. 2021).

11.2.2. ENVIRONMENTAL EFFECTS OF OFF-GRID MARINE RENEWABLE ENERGY APPLICATIONS

Most research and monitoring efforts that have examined potential effects of MRE single devices and small arrays on the marine environment have been focused on grid-scale devices designed to provide power for national electric grids. However, as the MRE industry progresses, it has become clear that there are many useful and profitable means to use MRE power for off-grid uses. These uses include generating and using power at sea such as powering ocean observation platforms and offshore aquaculture operations. Similarly, remote coastal locations and islands that are often powered by imported diesel fuel are excellent opportunities for a renewable energy transition focused around MRE. These remote or islanded areas generally have limited power needs that could be satisfied by a mix of renewable energy sources including MRE, microgrids, and energy storage. Research is ongoing to marry these off-grid uses with wave, tidal, ocean current, riverine, and OTEC devices. Most of these applications (except those that may benefit from OTEC power) will require smaller devices than have been previously designed and tested. These devices are likely to have less, or at least different, environmental effects from grid-scale devices. Small-scale and test deployments of MRE devices will be examined to determine the environmental effects through case studies, and a framework for consenting off-grid MRE devices among the OES-Environmental countries will be prepared. This information will be made available to regulators and developers to accelerate siting and consenting processes of smaller-scale devices.

11.2.3. SYSTEM-WIDE EFFECTS

During Phase 4 of OES-Environmental, initial steps were made to examine potential MRE effects beyond small numbers of devices, as well as to examine the role that MRE development will play in ecosystems and food webs, and the effect these interactions will have on other human uses of the ocean. This effort will continue through Phase 5, gathering new information as larger arrays are deployed and operated, and improving on the tools and data that can determine the integration of MRE with marine ecosystems, other ongoing anthropogenic stressors, and future uses of the oceans. As demonstrated in Chapter 10 on tropical ecosystems, there are many new interactions and potential effects that must be considered in tropical areas as countries deploy more devices, including OTEC and salinity gradient plants, for which little is known about potential effects. In addition, potential effects of an expanding MRE industry must be placed within the context of other offshore developments, and against the shifting baseline of climate change that will change ocean environments substantially over coming decades. The system-wide effects of large-scale development will be investigated with the addition of information from new studies and suitable surrogates, as well as those simulated with a range of models that provide insight into future outcomes. Projections of potential future effects and the state of the environment into which MRE will develop will assist planners and funders of projects in determining their feasibility, smoothing the way for larger array deployment.

11.2.4. SOCIAL AND ECONOMIC EFFECTS OF MARINE RENEWABLE ENERGY

Social and economic effects are inextricably tied up with environmental effects of MRE in the minds of stakeholders. As larger arrays are deployed and MRE projects are developed in a broader range of market applications, there will be a need to develop a deeper understanding of these social and economic effects, noting where societal interests intersect with the use and conservation of the marine environment. OES-Environmental will examine how different scales, locations, and end uses of MRE power can affect coastal communities and other stakeholders, developing best practices for assessments of social and economic effects. This information will be useful to the MRE industry because project success relies on social acceptance and the identification of potential impacts, and to the larger MRE community to work towards standardizing methods for data collection and assessment.

11.3. CONCLUSION

In 2010, when OES tasked OES-Environmental to investigate the environmental effects of MRE to facilitate consenting, and to document the material in a database, the expectation was that the key questions would all be answered within three to four years (NREL & NRCan 2007; Copping et al. 2013). The assumption was that by then, MRE arrays would contribute power to national grids, and regulatory processes for their deployment would become routine and simple. However, understanding the potential environmental effects of MRE single devices and arrays, mooring lines, foundations, anchors, generators, and surface floats has proven more intricate than anticipated. Currently, many countries still lack well-established regulatory pathways for MRE deployment, including regulation that focuses on monitoring and mitigation of potential environmental effects.

Throughout the investigation of the environmental effects of MRE, substantial insight has been gained into how marine animals, habitats, and ecosystem processes respond to the ever-growing use of the ocean, amidst shifting baselines due to climate change. Despite not being an initial objective of OES-Environmental, a global network comprising researchers, device and project developers, regulators, advisors, and other stakeholders has become established, collectively aiming to advance MRE as an important renewable energy source, while responsibly protecting the oceans. OES-Environmental takes pride in the collaborative efforts of participating countries within this network, with representatives from each country expressing confidence that the strides made thus far will soon pave the way for a thriving and sustainable global MRE industry.

11.4. REFERENCES

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