OES-ENVIRONMENTAL

2024
State of the Science Report

ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY
DEVELOPMENT AROUND THE WORLD

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SEPTEMBER 2024

A report prepared by Pacific Northwest National Laboratory on behalf of the U.S. Department of Energy (the OES–Environmental Operating Agent) and other participating nations under the International Energy Agency (IEA) Ocean Energy Systems (OES) intergovernmental collaboration.

SUGGESTED CITATION
Garavelli, L., Copping, A. E., Hemery, L. G., Freeman M. C., editors. 2024. OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). doi:10.2172/2438585

OES-Environmental 2024 State of the Science report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2024

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A PDF file of this report is available at: *https://tethys.pnnl.gov/publications/state-of-the-science-2024*

ACKNOWLEDGEMENTS

The authors would like to thank the U.S. Department of Energy and Ocean Energy Systems for their generous financial support for this effort. The countries that make up OES-Environmental contributed the in-kind time of their country representatives and other resources, without which this report would not have been possible.

We also want to thank Samantha Eaves, Denis Nault, Nina Joffe, and Sarah Loftus from the U.S. Department of Energy Water Power Technologies Office for their valuable input and feedback on the report, and acknowledge the support of Erin Trager, U.S. Bureau of Ocean Energy Management.

We are grateful to Amy Woodbury, Cailene Gunn, Miriam Blake, Dominick DeCanio, and Anita Waller from Pacific Northwest National Laboratory for assisting with OES-Environmental and the report.

We want to thank all the researchers and developers who have contributed information to the OES-Environmental metadata collection effort, the developers who provided images for third-party use to the Tethys Engineering Marine Renewable Energy Photo Library, as well as developers, researchers, and regulators who took the time to provide input to case studies and to carefully review the report.

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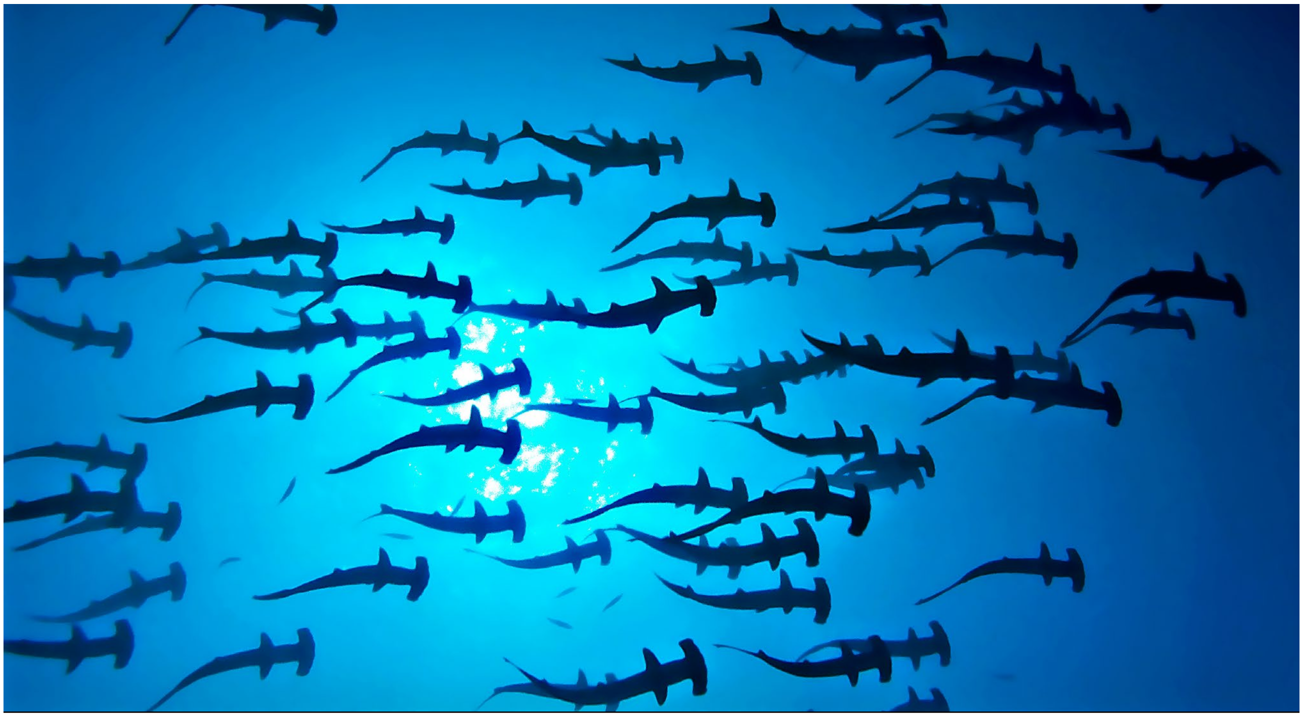


When citing this report in its entirety, please use the following citation:

Garavelli, L., Copping, A. E., Hemery, L. G., Freeman M. C., editors. 2024. OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). doi:10.2172/2438585

When citing individual chapter, please use the individual chapter citations below.

Section A – Introduction

Chapter 1
Marine Renewable Energy and Ocean Energy Systems-Environmental

Copping, A. E. 2024. Marine Renewable Energy and Ocean Energy Systems-Environmental. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 1-7). doi:10.2172/2438586

Chapter 2
Progress in Understanding Environmental Effects of Marine Renewable Energy

Copping, A. E and Hemery, L. G. 2024. Progress in Understanding Environmental Effects of Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 8-25). doi:10.2172/2438587

Section B – Updating the State of the Science

Chapter 3
Marine Renewable Energy: Stressor-Receptor Interactions

Garavelli, L., Hemery, L. G., Rose, D. J., Farr, H., Whiting, J. M., and Copping, A. E. 2024. Marine Renewable Energy: Stressor-Receptor Interactions. In L. Garavelli, A.E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 26-102). doi:10.2172/2438589

Section C – Human Dimensions of Marine Renewable Energy

Chapter 4
Social and Economic Effects of Marine Renewable Energy

Freeman, M. C., and Rose, D. J. 2024. Social and Economic Effects of Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 104-142). doi:10.2172/2438591

Chapter 5
Stakeholder Engagement for Marine Renewable Energy

Rose, D. J., and Freeman, M. C. 2024. Stakeholder Engagement for Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 144-169). doi:10.2172/2438593

Section D – Resources to Advance Marine Renewable Energy

Chapter 6
Strategies to Aid Consenting Processes for Marine Renewable Energy

Freeman, M.C. 2024. Strategies to Aid Consenting Processes for Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 170-203). doi:10.2172/2438595

Chapter 7
Education and Outreach around Environmental Effects of Marine Renewable Energy

Rose, D. J. 2024. Educational and Outreach around Environmental Effects of Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 204-216). doi:10.2172/2438596

Chapter 8
Marine Renewable Energy Data and Information Systems

Farr, H. 2024. Marine Renewable Energy Data and Information Systems. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 218-224). doi:10.2172/2438597

Section E – Beyond Stressor-Receptor Interactions

Chapter 9
Beyond Single Marine Renewable Energy Devices: A System-wide Effects Approach

Hemery, L. G., Hasselman, D. J., Le Marchand, M., Safi, G., Fulton, E. A., Copping, A. E. 2024. Beyond Single Marine Renewable Energy Devices: A System-wide Effects Approach. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 226-250). doi:10.2172/2438598

Chapter 10
Potential Environmental Effects of Marine Renewable Energy in Tropical and Subtropical Ecosystems

Garavelli, L., Hemery, L. G., Farr, H., Apolonia, M., Haywood, Z., Alamillo-Paredes, A., Bender, A. 2024. Potential Environmental Effects of Marine Renewable Energy in Tropical and Subtropical Ecosystems. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 252-271). doi:10.2172/2438599

Section F – Looking Ahead

Chapter 11
Summary and Path Forward

Copping, A. E. 2024. Summary and Path Forward. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 272-281). doi:10.2172/2438600

ABBREVIATIONS AND ACRONYMS

°C	degrees Celsius
μPa	micropascal(s)
μT	microtesla(s)
μV	microvolt(s)
AC	alternating current
AM	adaptive management
B-fields	magnetic field
BOEM	Bureau of Ocean Energy Management
CEA	cumulative effects assessment
cm	centimeter(s)
DC	direct current
E-fields	electric fields
EIA	environmental impact assessment
EMEC	European Marine Energy Centre
EMF	electromagnetic field
EwE	Ecopath with Ecosim (modeling approach)
FAIR	findable, accessible, interoperable, and reusable
FERC	Federal Energy Regulatory Commission
FORCE	Fundy Ocean Research Centre for Energy
GIS	geographic information system
IEA	International Energy Agency
iE-fields	induced electric field
IEC TC 114	International Electrotechnical Commission Technical Committee 114
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kHz	kilohertz
km	kilometer(s)
kV	kilovolt(s)
kW	kilowatt(s)
m	meter(s)
mm	millimeter(s)
MPA	Marine Protected Area(s)
MRE	marine renewable energy
MSP	marine spatial planning
mT	millitesla(s)
MW	megawatt(s)
MWh	megawatt-hour(s)
nm	nanometer(s)
NOAA	National Oceanic and Atmospheric Administration
nT	nanotesla(s)
OES	Ocean Energy Systems
ORJIP	Ocean Renewables Joint Industry Programme
OSMOSE	Object-oriented Simulator of Marine ecOSystem Exploitation model
OTEC	ocean thermal energy conversion
PAMEC	Pan American Marine Energy Conference
PNNL	Pacific Northwest National Laboratory
PRIMRE	Portal and Repository for Information on Marine Renewable Energy
s	second(s)
SEIA	social and economic impact assessment
SIA	social impact assessment
STEM	science, technology, engineering, and math
T	Tesla
UK	United Kingdom
US	United States
U.S. DOE	United States Department of Energy
V/m	volts per meter
W	watt(s)
WEC	wave energy converter

CONTENTS

FIGURES

TABLES

BOXES

LIST OF CASE STUDIES HIGHLIGHTED THROUGHOUT THE 2024 STATE OF THE SCIENCE REPORT

Executive Summary

This report summarizes the state of the science of environmental effects of marine renewable energy (MRE) and serves as an update and a complement to the *2020 State of the Science* report. While the research and monitoring findings prior to 2020 are summarized throughout, the main focus of the report is on the more recent work.

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). The *2024 State of the Science* report mainly 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 riverine turbines, but also includes new findings from environmental effects of ocean thermal energy conversion (OTEC) plants. Lessons learned from other offshore industries are included, where appropriate.

This report has brought together the most up-to-date information on potential environmental effects of MRE development, using information from public sources as well as new scientific research. The Ocean Energy Systems (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. This report encompasses an introduction and path forward, as well as nine chapters that provide details of research and monitoring findings around the world on environmental effects of MRE.

BENEFITS OF MARINE RENEWABLE ENERGY

MRE is a growing area of development, deployment, research, and financing due to climate change concerns. Up to 80% of the world's energy needs could be met by wind and solar, but the final 20% remains elusive. MRE can augment grid-scale energy in coastal areas, be the sole renewable source in remote areas, and create opportunities for offshore aquaculture and decarbonization.

POTENTIAL ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY PROJECTS AROUND THE WORLD

Over the past two decades, 86 projects with environmental baseline and post-installation monitoring have been identified globally, with the United Kingdom, Europe, and the Americas leading with the greatest numbers. Recommendations have been made to improve the outcomes of environmental effects studies by focusing on collecting baseline data, identifying risks early, collaborating with researchers and communities, and promoting transparency in data accessibility, to move the MRE industry forward.

MARINE RENEWABLE ENERGY: STRESSOR-RECEPTOR INTERACTIONS

Since 2020, progress has been made in understanding the major stressor-receptor interactions that help to delineate potential risks from MRE development.

A commonly used method of evaluating potential environmental effects of 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, or ecosystem processes that could be affected by stressors.

Collision Risk for Marine Animals around Turbines

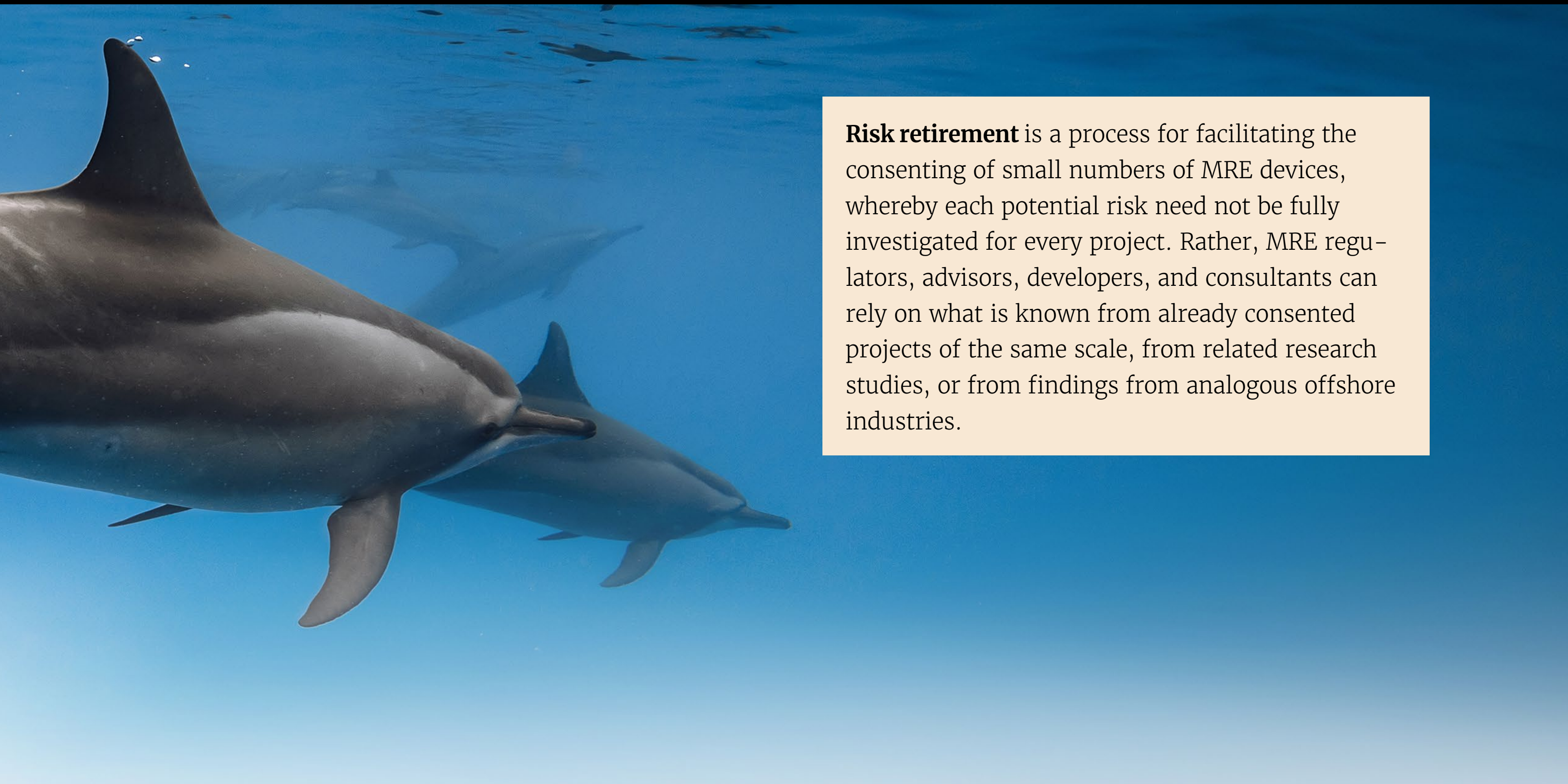
The risk of collision for marine animals with turbine blades remains a significant barrier to tidal and riverine energy project consenting. The outcome of collision risk involves a series of actions by the animal, including avoidance by swimming in the opposite direction, above, below, or around the turbine, or evasion at the last minute around the turbine. If these steps fail, a collision may occur. Increasingly, the use of underwater video is elucidating the risk of collision. While research has shown that adult salmon in a river are not likely to collide with riverine turbine blades, smolt may pass through the rotor swept area and become disoriented. Marine mammals have been observed avoiding operating tidal turbines. 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, as well as the more traditional collision risk and encounter risk models. 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
Underwater noise from turbines and WECs poses a risk to marine animals, most often through changes in their behavior, and suggests the need to monitor the amplitude and frequencies emitted. The International Electrotechnical Commission Technical Committee (TC114) provides guidance on accurate noise measurements around MRE devices. At present, monitoring suggests that operational noise is unlikely to harm marine animals for single devices and small arrays. New frameworks and modeling approaches for underwater noise from MRE devices further confirm this risk. This risk is considered to be retired for small numbers of devices (one to six).

Electromagnetic Field Effects from Power Cables and Marine Renewable Energy Devices
In the past four years, there have been few field investigations of potential electromagnetic field (EMF) effects from MRE systems on marine animals. Laboratory studies have shown behavior changes among EMF-sensitive marine species, including sharks, rays, skates, crabs, and lobsters. However, EMF emissions from export cables from MRE devices are generally considered below the level that will pose a significant risk level. This risk is considered to be retired for small numbers of devices (one to six).

Changes in Benthic and Pelagic Habitats Caused by Marine Renewable Energy Devices
Marine environment changes are inevitable with any MRE development, arising from the placement of devices, anchors, foundations, and cables. However, these changes are unlikely to cause significant harm if an MRE project is sited carefully. Studies have focused on understanding animal distribution, characterizing the composition of biofouling, implementing numerical models, or improving methodologies for monitoring habitats and communities. Despite knowledge gaps, the lack of evidence of harm to benthic and pelagic habitats has led to the risk being retired for small numbers of devices (one to six).

Changes in Oceanographic Systems Associated with Marine Renewable Energy Devices
Changes in oceanographic conditions due to the operation of turbines and WECs are generally being investigated using numerical models that examine changes in wave heights, water circulation, and water column stability. Field studies have not yielded results, as the changes are less than the natural variability of the system. For small numbers of devices (one to six), the risk should be retired. Risks associated with the operation of OTEC plants have been identified and can be mitigated with guidance from numerical models and proper engineering designs.



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 regulators, advisors, developers, and consultants can rely on what is known from already consented projects of the same scale, from related research studies, or from findings from analogous offshore industries.

Entanglement Risk with Marine Renewable Energy Mooring Lines and Cables

The risk of large marine animals getting entangled in mooring lines or cables between MRE devices is theoretical, with no evidence of entanglement observed to date. Stakeholder concerns persist due to the effects of lost fishing gear and worries about floating offshore wind platforms. As larger arrays are deployed, monitoring may provide more insights.

Displacement of Animals from Marine Renewable Energy Development

Displacement may occur when marine animals respond to stressors, disrupting movement patterns of migratory and resident marine species. Larger MRE arrays may disrupt these species' movements, but data will not be available until larger arrays are deployed. A framework and recommendations are laid out to address displacement, particularly knowledge gaps, as the MRE industry grows.

SOCIAL AND ECONOMIC EFFECTS OF MARINE RENEWABLE ENERGY

Research on the social and economic effects of MRE development has not been extensive, with data often lacking or being unsuitable for specific locations or communities. However, studies have examined benefits and negative impacts on other users of the ocean, coastal communities, and Indigenous people. As MRE development expands, data on effects should be collected.

STAKEHOLDER ENGAGEMENT FOR MARINE RENEWABLE ENERGY

Engaging stakeholders in MRE projects early in the planning and development process increases the likelihood that communities will accept and support a project. This includes legally mandated informing and involving stakeholders, as well as preferred practices that involve local communities and seek to provide employment for those with beneficial skills. Successful stakeholder engagement processes involve implementing best practices and measuring outcomes.

STRATEGIES TO AID CONSENTING PROCESSES FOR MARINE RENEWABLE ENERGY

Since 2020, OES-Environmental has focused on presenting the science behind the potential risks of MRE development on marine animals, habitats, and ecosystem processes. The risk retirement process includes methods for data transferability, allowing datasets from one location to be relevant to new projects. Four stressor-receptor interactions have been identified that can be retired for small number of MRE devices: underwater noise, EMFs, changes in habitat, and changes in oceanographic systems. Guidance documents and strategies for applying existing knowledge have been developed, including adaptive management, marine spatial planning, and tools tailored for individual nations.

EDUCATION AND OUTREACH AROUND ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY

MRE is not well known to the public, supporting the need for education and outreach to a variety of audiences, including children, high school students, and other audiences. OES-Environmental has created materials, including coloring pages, podcasts, videos, presentations, and social media posts to support this effort. Along with one-on-one discussions with interested parties, these materials are used to spread awareness about the benefits, challenges, and opportunities of MRE, fostering support and advocacy for renewable energy technologies.

MARINE RENEWABLE ENERGY DATA AND INFORMATION SYSTEMS

The MRE industry is beginning to generate vast amounts of data from device testing, environmental monitoring, and laboratory experiments. The United States has created the Portal and Repository for Information on Marine Renewable Energy (PRIMRE), to support curating, storing, and disseminating data and information. PRIMRE includes Tethys, which supports environmental studies on MRE and OES-Environmental activities. MRE data and information systems also exist in other nations.

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

The MRE industry is beginning to move from single to multiple devices, with plans for large-scale commercial arrays. To understand potential environmental effects, strategies for scaling knowledge from single devices to arrays are examined. Ecosystem indicators and models are examined for their ability to also account for MRE development effects, and a framework has been developed for assessing cumulative effects on the marine environment by MRE development in the context of other human activities.

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

MRE is growing in several tropical and subtropical countries, with an increased focus on OTEC, salinity gradients, and wave energy devices. Most of our present knowledge has been derived from temperate regions. Tropical and subtropical ecosystems have higher biodiversity and complex food webs, necessitating a different approach to their assessment, in addition to knowledge transfer from existing research.

PATH FORWARD FOR MARINE RENEWABLE ENERGY RESEARCH

The body of knowledge that has been gleaned over the past 14 years (2010–2024) of OES-Environmental represents a level of understanding that can be used to facilitate consenting of single devices and small arrays, as well as providing insight on how larger arrays might fit into the receiving environment. The next phase of OES-Environmental focuses on four areas: environmental acceptability, environmental effects of off-grid MRE applications, system-wide effects, and social and economic effects of MRE.

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Section A

INTRODUCTION

1.0

Marine Renewable Energy and Ocean Energy Systems–Environmental

Author: Andrea E. Copping

For many countries, marine renewable energy (MRE) is the most recent entry into their renewable energy portfolio. MRE involves the generation of energy from the movement of seawater including tides, waves, and persistent ocean currents, as well as from the gradients of temperature and salinity in the oceans. Some countries also include energy generation from the open waters of large rivers as part of MRE. Each MRE resource requires a different type of device to harvest that energy, placed in the appropriate portion and depth of the ocean or large river and secured to the seabed either by weight or by anchors. At full scale, these devices are large; Figure 1.1 puts the size of these devices in the context of other technologies and well-known landmarks for scale. The MRE devices generally represent the largest devices available.

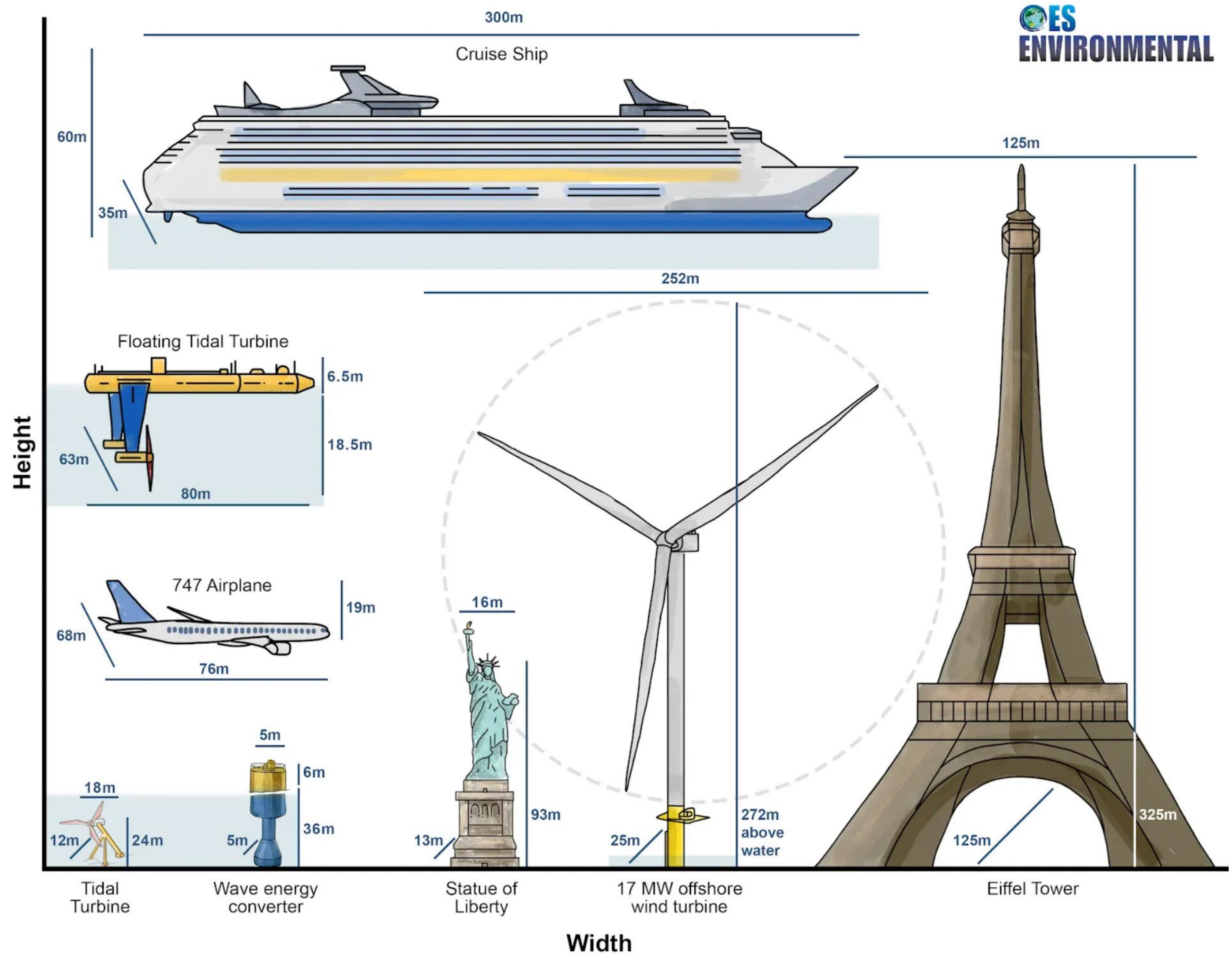

Figure 1.1. Size comparison of marine renewable energy (MRE) devices (a bottom-based tidal turbine, a floating tidal turbine, and a floating wave energy converter) with other technologies and well-known landmarks. The MRE devices generally represent the largest devices available. (Illustration by Stephanie King)

1.1. BENEFITS OF MRE

MRE continues to be an active area of development, deployment, research, and financing. With accelerating concerns about the effects of climate change, cultivating new renewable and sustainable energy sources has become more urgent in developed and developing countries. It has been estimated that as the world transitions to renewable energy forms, up to 80% of the world's energy needs could be met by wind and solar energy (Bogdanov et al. 2021). The final 20% remains elusive and MRE is suited to fill much of this need. MRE can be used to augment grid-scale energy in coastal areas, and also as the sole renewable source of energy in remote coastal areas and for islands (LiVecchi et al. 2019). Additional opportunities can be created at sea, including powering offshore aquaculture, extending the missions for ocean observations, extracting critical minerals from seawater, decarbonizing shipping, and other blue economy uses (Copping et al. 2019).

1.2. ENVIRONMENTAL RISKS OF MRE DEVELOPMENT

Wave energy converters (WECs), turbines for deployment in tidal, riverine, and ocean current areas, and ocean thermal energy conversion (OTEC) plants are in various stages of development throughout the world, and multiple different types of devices are under consideration. However, questions remain about the risk that the operation of these devices might pose to marine animals, habitats, and ecosystem processes. These potential effects continue to create uncertainty around the regulatory processes required to protect ocean resources and ensure that present uses of the ocean, such as fishing, boating, navigation, and cultural uses are protected.

The potential environmental effects of MRE can be assessed systematically within the framework of stressor and receptor interactions (Boehlert & Gill 2010), where stressors are the MRE devices or other parts of the associated systems (anchors, floats, mooring lines, foundations, cables) that may cause stress, injury, or death to marine animals or habitats, or disrupt ecosystem processes. The receptors include marine animals, with particular emphasis on marine mammals, fish, sea turtles, and seabirds; marine habitats that support these and other species; and biotic and abiotic portions of the marine ecosystem processes that function together to create the living ocean. After more than a decade of research, there is a consensus among MRE researchers that there are seven key stressor-receptor interactions potentially affecting marine animals, habitats, and ecosystem processes (Figure 1.2):

- **Collision risk** - Risk of marine animals colliding with rotating turbine blades and other moving parts of MRE devices.
- **Underwater noise** – Disruption of marine animal navigation and communication from the noise of operational MRE devices.
- **Electromagnetic fields (EMFs)** – Disruptions to marine animal movement and behavior due to EMF emissions from energized power export cables.
- **Changes in habitats** – Alterations in benthic or pelagic habitats that support marine animals from the presence and operation of MRE devices.
- **Entanglement** – Risk of large marine animals becoming entangled in mooring lines or draped cables in the water column.
- **Changes in oceanographic systems** – Decreases in wave heights or changes in ocean water circulation due to the presence and operation of MRE devices.
- **Displacement** – Changes in the migratory pathways or other movements of marine animals due to the presence and operation of many MRE devices.

The status of knowledge about each of these interactions will be examined in detail in Chapter 3 of this report.

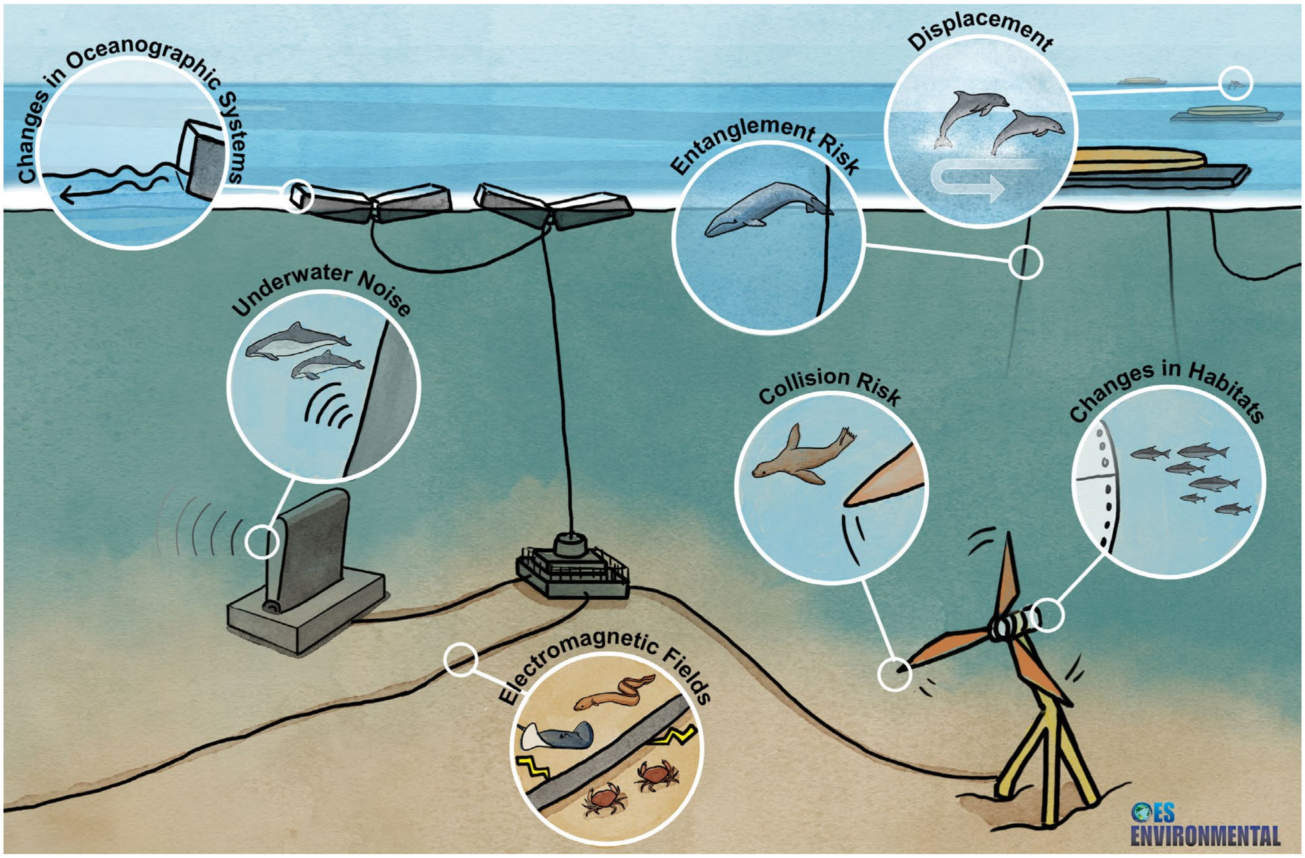

Figure 1.2. Stressor-receptor interactions potentially arising from various marine renewable energy devices. (Illustration by Stephanie King)

1.3. OES-ENVIRONMENTAL

OES-Environmental is a coalition of 16 countries focusing on the examination of the environmental effects of MRE. OES-Environmental is a task enabled by Ocean Energy Systems (OES), a Technology Collaboration Programme of the International Energy Agency, consisting of 25 countries and the European Commission committed to developing MRE for the benefit of their countries and the world. OES authorized OES-Environmental for a fourth phase over the period 2020–2024. This report provides an update of the state of the research and understanding of the effects of MRE as they affect consenting or permitting (hereafter consenting) in OES countries. The U.S. Department of Energy's Water Power Technologies Office leads OES-Environmental, in cooperation with the National Oceanic and Atmospheric Administration and the Bureau of Ocean Energy Management. The task is implemented by the U.S. Department of Energy's Pacific Northwest National Laboratory.

The goal of OES-Environmental is to understand and resolve the risks of MRE development and operation to the marine environment to accelerate the deployment of devices in a responsible manner. The 16 countries under OES-Environmental strive to reach this goal via:

- continuous international collaboration among representatives of the OES-Environmental countries to support international efforts and leverage international knowledge expertise;
- data collection and curation on the Tethys online platform;
- dissemination of knowledge and information broadly; and
- international engagement with stakeholders, developers, regulators, and advisors.

At the end of the third phase of OES-Environmental, the *2020 State of the Science* report (Copping & Hemery 2020) documented the state of the knowledge of the environmental effects of MRE to that date. Throughout Phase 4 (2020–2024), the knowledge gathered was disseminated and used to develop publications and engagement opportunities, including:

- translating the *2020 State of the Science* Executive Summary from English to five other languages;
- creating 13 Short Science Summaries that condense the information about individual stressor-receptor interactions and strategies for addressing them;
- recording five podcasts about MRE and its environmental effects;
- developing four videos hosted on YouTube that describe environmental interactions with MRE; and
- writing a 24-page MRE brochure designed to provide new regulators with a primer about these topics.

A significant amount of time during Phase 4 of OES-Environmental was devoted to building out the concept of risk retirement of stressor-receptor interactions that complicate consenting processes (see Chapter 6). Risk retirement, in the context of facilitating consenting for small MRE deployments, means that each potential risk need not be fully investigated for every project, but rather that MRE developers, consultants, regulators, and advisors rely on what is known from already consented projects, from related research studies, or from findings from analogous offshore industries (Copping et al. 2020). Risk retirement will not take the place of any existing regulatory processes, nor will it completely replace the need for appropriate data collection before and after MRE device deployment. As new information becomes available, for example as larger arrays are deployed, additional examination may be required for stressor-receptor interactions that were considered retired for small numbers of devices.

OES-Environmental developed several subsystems for the risk retirement process:

- **Risk Retirement Pathway** – an organized methodology for working through consenting processes, applying datasets at strategic times, and providing "off ramps" that allow particular stressor-receptor interactions to be "retired" for the purposes of consenting.
- **Data Transferability** – a process for the discovery and comparison of datasets and information from consenting MRE projects, studies, or other industries to determine whether they can be applied to new project applications.
- Best Management Practices for applying data transferability processes.
- **Monitoring Datasets Discoverability Matrix** – an interactive tool that catalogs existing datasets and provides location or contact information for obtaining the datasets.

- **Evidence Bases** – databases of the most relevant information from research papers and monitoring data that support risk retirement for specific stressor-receptor interactions.
- **Guidance Documents** – documents that move the content of scientific publications and knowledge into formats accessible to MRE developers, consultants, regulators and advisors, including the overall pathway, interaction-specific information, and country-specific documents that reflect differences in national regulations.

During Phase 4, OES-Environmental completed:

- risk retirement for four stressor-receptor interactions for small numbers of devices;
- guidance documents that address the overall process, six stressor-receptor interactions, and 13 countries; and
- evidence bases for six stressor-receptor interactions.

Outreach and engagement with stakeholders allow OES-Environmental to disseminate information about the environmental effects of MRE, as well as gather and assimilate the most up-to-date findings from around the world. During the COVID pandemic, OES-Environmental rapidly switched many of the planned in-person activities to online activities, and increased the communication and outreach to the MRE community during a time of limited in-person engagement. During Phase 4, OES-Environmental:

- hosted 17 webinars,
- delivered 23 conference presentations (online and in-person),
- organized and hosted 14 workshops,
- published six journal publications and four conference papers,
- organized three environmental effects tracks at conferences, and
- organized and hosted four online expert forums.

OES-Environmental also began to look at the potential environmental effects of MRE at larger scales. The majority of available information about stressor-receptor interactions is concerned with single devices or very small arrays, generally six or fewer devices. Three white papers and accompanying journal publications were prepared by OES-Environmental country representatives about topics that look to the future of MRE development:

- scaling the understanding of the effects of MRE development from single devices to arrays (Hasselman et al. 2023),
- investigating the effects of MRE on ecosystems in a holistic approach, and
- examining the cumulative effects of MRE combined with other anthropogenic activities.

Research and collection of monitoring data around deployed MRE devices have been derived largely from projects and studies in temperate areas of the world's oceans. MRE development in tropical and subtropical areas is becoming of increasing interest to governments and stakeholders around the world. OES-Environmental has examined the body of knowledge about environmental effects and determined that additional approaches beyond those applied to temperate areas are needed for tropical and subtropical ecosystems. These ecosystems host a diverse range of habitats and species compared to temperate ecosystems and have higher biodiversity (Myers et al. 2000). In the tropics, OTEC has emerged as a potentially viable renewable energy source for coastal areas and islands. OTEC may create new challenges for the marine environment that differ from those of turbines and WECs (see Box 1.1).

1.4. 2024 STATE OF THE SCIENCE REPORT

The culmination of Phase 4 of OES-Environmental is the preparation of this document, the *2024 State of the Science* report. The remainder of this report is organized as follows:

- Chapter 2 provides a summary of the MRE projects around the world for which environmental effects have been assessed.
- Chapter 3 examines the status of our understanding of the effects that MRE devices and development have on the marine environment, from the perspective of the effects of the various stressors of these systems on marine animals, habitats, and ecosystem processes.
- Chapter 4 addresses the social and economic effects of MRE development.
- Chapter 5 looks at the importance of stakeholder engagement related to MRE development.
- Chapter 6 summarizes key strategies for facilitating the consenting of MRE devices, including risk retirement,

data transferability, guidance documents, adaptive management, and marine spatial planning.

- Chapter 7 summarizes the outreach and engagement activities around the environmental effects of MRE.
- Chapter 8 presents the key data and information systems pertinent to MRE development.
- Chapter 9 examines the environmental effects of MRE beyond single devices, including scaling up effects of arrays, ecosystem effects, and the cumulative effects of MRE development combined with other anthropogenic stressors.
- Chapter 10 brings information forward about the potential environmental effects of MRE in tropical and subtropical ecosystems.
- Chapter 11 summarizes key points from the report and looks forward at pathways for the future development of MRE.

BOX 1.1.

OCEAN THERMAL ENERGY CONVERSION

Ocean thermal energy conversion (OTEC) harvests power from the ocean through a heat exchange process between warm surface water and cold deep water. OTEC provides the only MRE baseload power source, as the process of bringing cold and warm water together is continuous, unlike most other renewable energy sources. A temperature differential of at least 20°C is needed, which can only be achieved year-round in tropical areas. OTEC plants can be built on land, bringing the water to shore, or on floating platforms with an export power cable to shore. Deep ocean water from 800–1000+ m must be piped to the surface to be processed with warm surface water through heat exchangers, providing power to a turbine (Figure 1.3). The warm and cold water must then be returned to the ocean. The return of large volumes of cold water to the surface ocean has the potential to temperature-shock all living organisms and destabilize the water column above the thermocline. To mitigate these potential effects, the discharge of cold water is planned to occur at an intermediate depth that will allow for its mixing with ambient water and sinking to depth without causing harm to the oceanography of the region. While deep ocean water is rich in nutrients that could be used to enhance aquaculture, it is also high in carbon, which would further exacerbate carbon dioxide in surface ocean waters unless it is segregated and returned to depth or stripped of the carbon before being released into the surface ocean or atmosphere. Other effects include potential damage from shore-based OTEC plants, such as laying water pipes through coral reefs and nearshore habitats which must be avoided. Floating plants with power export cables could cause similar challenges related to the effects of electromagnetic fields on sensitive marine species.

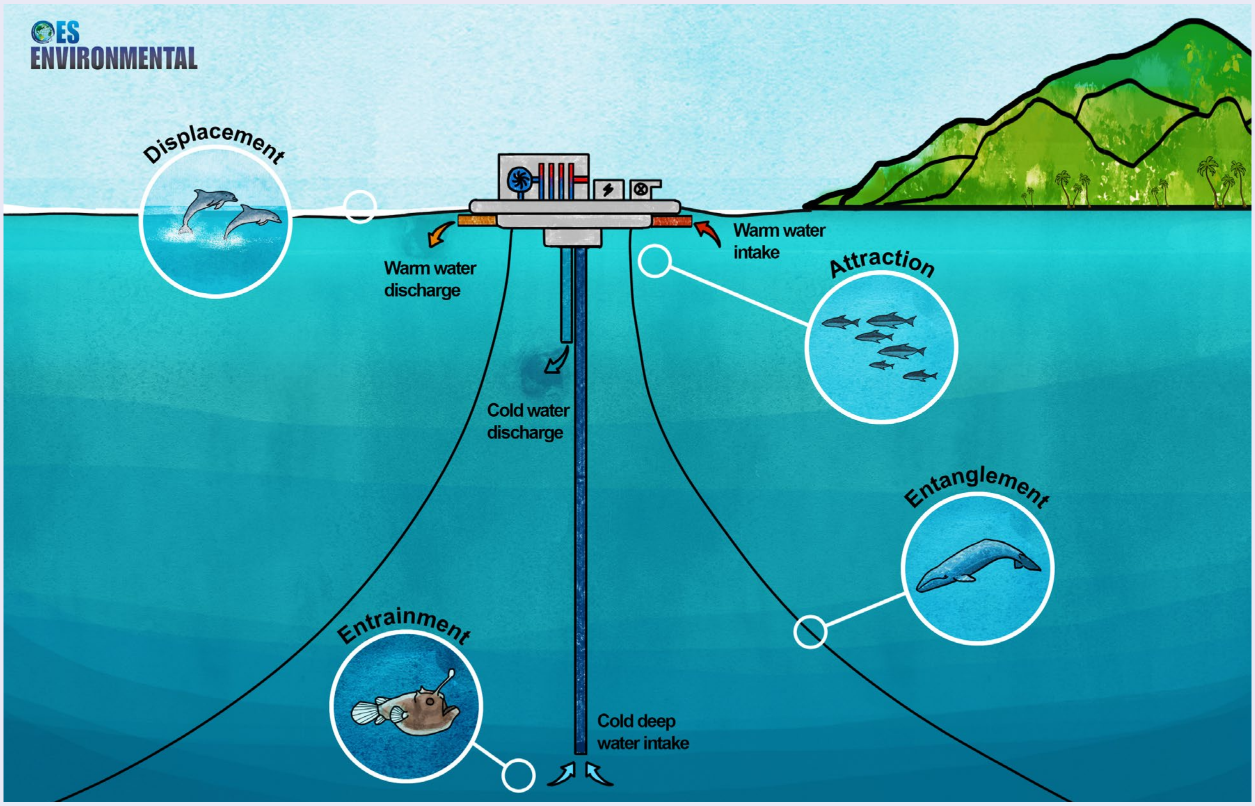

Figure 1.3. Water intake and discharge system of a floating ocean thermal energy conversion plant and potential environmental effects associated with the technology. (Illustration by Stephanie King)

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Suggested citation:

Copping, A. E. 2024. Marine Renewable Energy and Ocean Energy Systems-Environmental. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 1-7). doi:10.2172/2438586

2.0 Progress in Understanding Environmental Effects of Marine Renewable Energy

Authors: Andrea E. Copping, Lenaïg G. Hemery

Over the past two decades, researchers, in collaboration with the marine renewable energy (MRE) industry and regulatory agencies, have examined the potential effects of MRE, focusing on the stressor-receptor approach to categorize the most significant potential risks for tidal stream, riverine, persistent ocean currents, and wave energy devices (Copping et al. 2024). Recent interest in examining potential effects of ocean thermal energy conversion (OTEC) and salinity gradient energy production has initiated investigations in those areas as well.

The research areas that have received the greatest attention are those stressor-receptor interactions for which a high degree of uncertainty exists around the probability of the interaction occurring and/or the severity of the consequences, should the interaction occur. These high priority areas for all MRE devices or systems are:

- Collision risk of marine animals with rotating turbine blades (only of importance for tidal, ocean current, and riverine);
- Effects of underwater noise on animal behavior and health;
- Effects of electromagnetic fields (EMFs) from energized power export cables on animal behavior;
- Changes in benthic and pelagic habitats that affect marine animals;
- Entanglement of large marine animals in mooring lines or cables;
- Changes in oceanographic systems from operational MRE devices and arrays; and
- Displacement of marine animals due to the presence or operation of MRE devices and arrays.

These seven stressor-receptor interactions of high priority are further detailed in Chapter 3, which provides updates on the current knowledge on the interactions and potential risks to animals.

2.1. CONSIDERATIONS FOR DEPLOYMENT OF MRE DEVICES

Before deploying MRE devices, developers need to characterize the energy resources in the area, examine the hydrographic conditions, survey the seabed, assess potential hazards at the project site, measure the distance to the planned offtaker such as a grid or microgrid connection (LiVecchi et al. 2019), as well as consider factors such as the existing uses of the area, the proximity to ports for installation and maintenance, and the prevailing attitude of nearby communities (Wojtarowski et al. 2021). Understanding the potential risks to the marine environment is also a necessary step to move toward regulatory approval for deployment and operation.

Regulatory approval for MRE deployment typically requires baseline assessments of the marine animals, plants, and habitats in proximity to the project site, with the need to also consider the bathymetry, proximity to the coast and other bodies of water, coastal geometry, coastal dynamics, and the presence of other sea users (Cradden et al. 2016). Among the jurisdictions developing MRE, most require post-installation monitoring for potential effects (Eaves et al. 2022).

2.2. EVALUATING PROGRESS IN EXAMINING ENVIRONMENTAL EFFECTS OF MRE

The collection of Ocean Energy Systems (OES)-Environmental Metadata Forms, hosted on the Tethys platform, documents past and present MRE projects for which environmental sampling, monitoring, and analysis information is available (Whiting et al. 2019). While some of the projects are associated with project planning phases, most reflect deployments in the ocean and/or large rivers. The metadata forms have been collected continuously since 2010 and reflect the longest record of environmental-effects investigations for the MRE sector internationally. The collection includes deployments at test sites around the world, pilot and small-scale demonstration projects that remain for short periods of time in the water, and larger commercial projects. As of May 2024, there are 144 metadata forms available online on Tethys, reflecting tidal stream, wave, ocean current, riverine, OTEC, and salinity gradient deployments.

Eighty-six projects were identified globally with environmental assessments, post-installation monitoring, or extensive planning for monitoring in advance of deployment (Figure 2.1, Table 2.1). Other metadata forms did not have sufficient information to allow for their inclusion in the analysis. Of those 86 included projects, 40 were tidal, 39 were wave, two were ocean current (in advanced planning stages), and five were riverine projects.

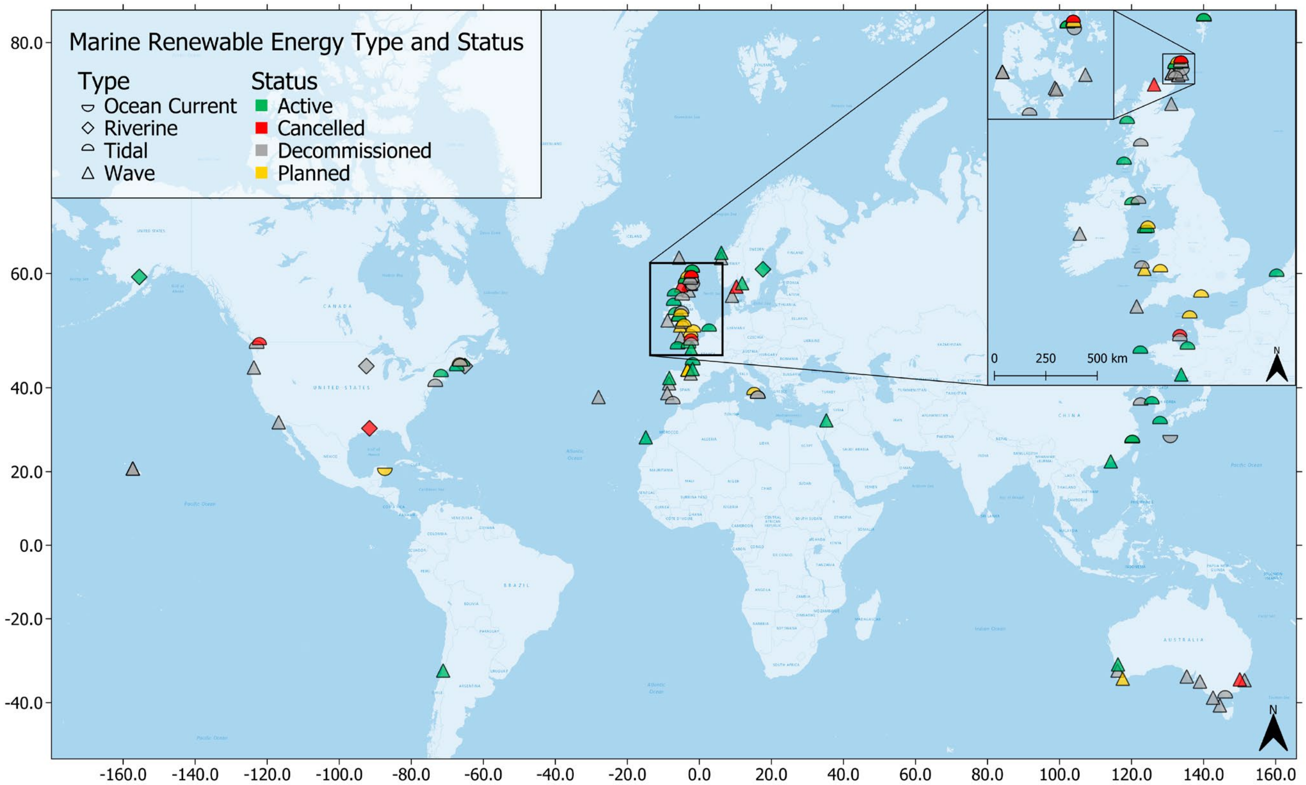


Figure 2.1. Marine renewable energy projects around the world with associated records of environmental monitoring, separated by type of technology and status of development.

Collision risk, underwater noise measurements, experiments to determine effects of EMFs, and measurements of change in benthic habitats are the most common areas of research. As documented in Copping et al. (2024), the effects that were most commonly investigated were for these four stressor-receptor interactions. Although these effects were seldom (if ever) documented, the most commonly expected effects might be, in no particular order, altered behavior of the fauna potentially resulting in bioenergetic effects; changes in predation or competition levels; changes in migratory routes; population failures; injuries or death of individuals; changes in biodiversity and food webs; establishment of invasive species; degradation of habitats; shoreline modifications; and changes in ecosystem connectivity. Entanglement risk, changes in oceanographic systems, and displacement of marine animals have not often been measured directly, although extensive numerical modeling of hydrodynamic changes in ocean systems due to the placement of MRE devices has created a large body of work.

2.3. CASE STUDIES OF MRE PROJECTS

The recent paper by Copping et al. (2024) systematically examined progress in investigating environmental effects of MRE, examining each project by region and country for the stage of development, progress on environmental assessment and monitoring, and the specific stressor-receptor interactions that have been considered. The authors set out to determine the effectiveness of environmental assessment and monitoring around MRE devices and arrays. They created a framework that seeks to evaluate the quality and outcomes of environmental assessment data collection, analysis, and interpretation for projects represented by the OES-Environmental metadata forms. The framework includes information on the:

- **Level of monitoring** – duration of monitoring activities; whether baseline assessment and post-installation monitoring were carried out; and what types of accepted methods were used.
- **Outputs of the monitoring** – citations from research reports and peer-reviewed papers; government reports; conference papers; and other products such as open-access datasets.

Table 2.1. Environmental monitoring for potential MRE effects, by region and country. Most deployments have been of short duration for testing, while others are in late stages of planning for commercial deployment. For the United Kingdom, devices tested at the European Marine Energy Centre (EMEC) were listed apart from those deployed in the rest of the country.

REGION	Country	Type of Technology	Phase of Development	Collison Risk	Underwater Noise	Electromagnetic Fields	Habitat Changes	Oceanographic Systems	Displacement	Other
EUROPE	France	4 Tidal	3 tested and decommissioned; 1 planned	●	●	●	●	●		
	Ireland	1 Wave	Tested and decommissioned							Baseline assessment of fauna
	Italy	1 Tidal	Tested and decommissioned		●					
	Netherlands	1 Tidal	Operational						●	Movement of fauna
	Norway	3 Wave	1 operational; 2 tested and decommissioned	●	●	●	●	●	●	
	Portugal	2 Wave	1 operational; 1 tested and decommissioned		●	●	●		●	Sediment transport
	Spain	3 Wave	1 operational; 1 tested and decommissioned; 1 planned		●	●	●	●		
	Sweden	Multiple wave devices tested at two sites	1 operational; 1 tested and decommissioned		●		●		●	Sediment sampling
	Sweden	1 Riverine	Operational	●	●					
UNITED KINGDOM		14 Tidal	7 operational; 3 tested and decommissioned; 1 tested and not recovered; 3 planned	●	●		●		●	
		4 Wave	3 tested and decommissioned; 1 planned	●	●		●	●		
		7 Tidal	5 tested at EMEC and decommissioned; 2 operational	●	●		●	●	●	Navigation, human dimension
		7 Wave	6 tested at EMEC and decommissioned; 1 tested and lost at sea	●	●		●		●	Atmospheric emissions, fisheries impacts, navigation, entanglement
AMERICAS	Canada	8 Tidal	5 tested and decommissioned; 1 tested and not recovered; 2 planned	●	●		●		●	Human dimensions
	Canada	2 Riverine	2 tested and decommissioned	●						
	Chile	1 Wave	Operational				●			Baseline assessment of fauna
	Mexico	1 Ocean current	Planned	●			●		●	
	United States	3 Tidal	1 operational; 2 tested and decommissioned	●	●		●	●	●	
	United States	4 Wave	4 tested and decommissioned		●					
	United States	2 Riverine	1 operational; 1 tested and decommissioned	●			●	●		
ASIA	China	1 Wave	Operational		●			●	●	
	Japan	1 Tidal	Tested and decommissioned					●		Fisheries interactions
OCEANIA	Australia	9 Wave	7 tested and decommissioned; 1 tested and not recovered; 1 planned		●		●		●	Baseline assessment of fauna
	Australia	1 Tidal	1 tested and decommissioned		●					Water quality, impacts on flora and fauna, vibration
MIDDLE EAST	Israel	1 Wave	Operational				●			

- **Outcomes or uses of the monitoring results** – whether specific risks were retired or mitigation was required; whether concerns about potential environmental effects led to delays or cancellation of the project; and whether the consenting outcomes were linked to the monitoring results.

This framework was used to evaluate five case studies for which sufficient data were available to determine the effectiveness of the research on environmental effects of MRE. The five case studies included two tidal, two wave, and one riverine projects (Copping et al. 2024):

1. Tidal energy development by MeyGen in the Inner Sound, Pentland Firth, Scotland, United Kingdom (UK), with a focus on collision risk, underwater noise, and electromagnetic fields.
2. Tidal energy development by Nova Innovation in Bluemull Sound, Shetland Islands, Scotland, UK, with a focus on collision risk.
3. Wave energy development MARMOK-A-5 by IDOM at the Spanish test site BiMEP (Biscay Marine Energy Platform), with a focus on underwater noise and EMF.
4. Wave energy development by various technology developers at the Swedish test site Lysekil, with a focus on underwater noise and habitat changes.
5. Riverine energy development RivGen® by Ocean Renewable Power Company (ORPC) near the village of Igiugig, Alaska, United States (US), with a focus on collision risk.

Each of the five case studies is recapped here, with additional focus on the methods of data collection and monitoring results, where applicable. A summary of these projects is shown in Table 2.2.

Table 2.2. Summary of examples of deployment sites where environmental monitoring has taken place.

Project	Year of setup	Type of energy	Country	Environmental studies	Results
MeyGen Tidal Energy Project	2007	Tidal	Scotland, United Kingdom (UK)	Collision risk marine mammals and diving seabirds; noise; EMF; sediment transport.	Marine mammals avoid the operational turbine; some seals swam nearby; EMF and noise not significant; no significant changes in sediment transport.
Nova Innovation Shetland Tidal Array	2016	Tidal	Shetland Islands, Scotland, UK	Collision risk marine mammals and diving seabirds; seabed surveys. Surveys carried out for marine mammals and seabirds and noise.	When turbine not moving: harbor seals, diving seabirds, and fish swimming in close proximity; with blades rotating, they move away or are not present. Noise and disturbance considered not significant.
IDOM's MARMOK Wave Energy Converter	2016	Wave	Spain	Underwater noise; EMF emissions; changes in seafloor integrity.	No EMF emissions; no significant changes in seafloor integrity; noise lower than normal underwater noise.
Lysekil Wave Energy Test Site	2006	Wave	Sweden	Changes in habitats; underwater noise; displacement.	Little change in the seafloor; new habitats; noise levels were deemed not likely to trigger behavioral responses.
Igiugig Riverine Turbine Project	2014	Riverine	Alaska, United States	Impact on sockeye salmon population.	Adult salmon not affected; some smolts swam through the turbine and were disoriented.

2.3.1.
MEYGEN TIDAL ENERGY PROJECT

As of 2024, the MeyGen Tidal Energy Project (MeyGen), located in the Pentland Firth between the Orkney archipelago and mainland Scotland (Figure 2.2), represents the largest tidal array in the world that has deployed full-scale devices (MeyGen 2012; SAE 2024). Baseline monitoring began in 2007 and continued until the first turbines were installed in 2016 (Black and Veatch 2020; Williamson et al. 2016). After installation, monitoring began for potential collision risk of marine animals, particularly marine mammals and diving seabirds (e.g., Johnston et al. 2021; Palmer et al. 2021), in addition to examining the underwater noise and EMF emissions from the cables, and modeling of sediment transport in Pentland Firth.

The research team used an integrated instrument platform that collected passive and active acoustic data to monitor marine mammals and other mobile species (Gillespie et al. 2022; Gillespie et al. 2023). The platform was cabled to provide power and data transmission to shore. An array of hydrophones on the platform recorded harbor porpoise vocalizations, while high frequency multibeam sonars were used to investigate seal behavior around the operational turbine. The research team showed that marine mammals actively avoided the operating turbine, although some individuals swam close to the turbine (Gillespie et al. 2020, 2021; Palmer et al. 2021). Current work investigating seal behavior and quantifying their avoidance on a localized scale (10's of meters) is being undertaken by the same team. The regulators considered that EMF levels were

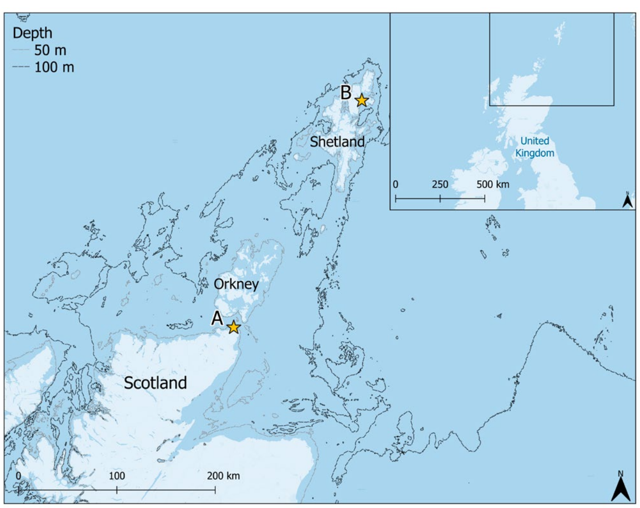


Figure 2.2. Locations of the MeyGen Tidal Energy Project (A) and the Nova Innovation Shetland Tidal Array (B) in Scotland, United Kingdom (yellow stars).

too low to cause harm to marine animals and the risk was retired (see Chapter 3). However, it was decided to assure that marine animals would receive the minimum EMF exposure possible by keeping the cables below the seabed wherever possible, either by the cables passing through boreholes or laid within natural crevices and cracks within the seabed (MeyGen 2015). Underwater noise was measured during installation and operation of the MeyGen turbines with the hydrophone on an integrated platform (Risch et al. 2020, 2023) but was only considered to be a risk during installation from piling; regulators required a soft start for installation procedures to reduce noise when possible (MeyGen 2012). Modeling efforts for sediment transport demonstrated the needs of many more turbines than are consented at MeyGen to show significant changes (Karunarathna et al. 2015).

Presently, MeyGen has four 1.5-MW devices in the water, and consent for up to 86 MW. The results of monitoring around the first four turbines have been directed at understanding the risk of collision for marine animals with the operational turbines and will provide the basis for regulators allowing the expansion to the full 86-MW build-out.

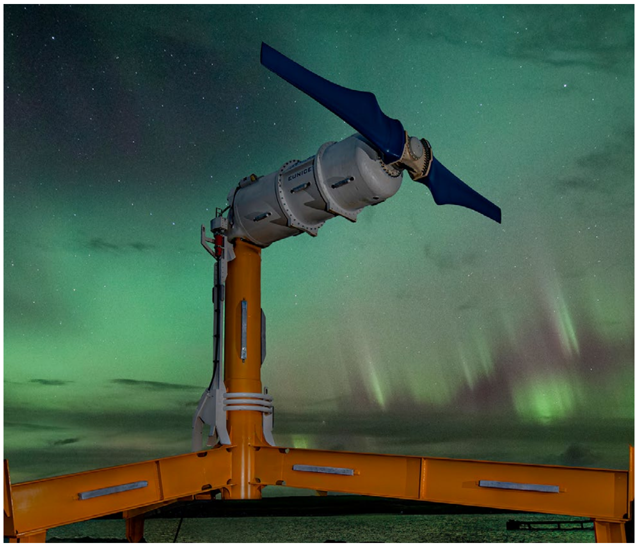
2.3.2.
NOVA INNOVATION SHETLAND TIDAL ARRAY

The Shetland Tidal Array (Nova Innovation) located in Bluemull Sound in the Shetland Islands (Figure 2.2), was the world's first grid-connected offshore tidal array. It also became the world's first baseload tidal power station in 2018 with the addition of battery storage facilities. The first three geared turbines were deployed in 2016 and 2017. A direct drive turbine was installed in 2020 with two further direct drive turbines in 2023, delivering a total six-turbine array capacity of 600 kW. The three original geared turbines were decommissioned in 2023 as part of the EnFAIT project to demonstrate and gather knowledge on the full lifetime of a tidal stream array. As of 2024, the Shetland Tidal Array comprises three direct drive turbines and associated onshore energy storage and EV charging facilities. Land-based surveys to gather data on the presence, abundance, and behavior of marine birds and marine mammals began in 2010 prior to turbine installations, continuing until July 2023 (Smith 2024).

Baseline seabed surveys using drop-down cameras were also carried out (McPherson 2015). After installation of the first turbines, monitoring was required under conditions of project licenses, set out in a Project Environmental Monitoring Plan (PEMP) that has evolved throughout the lifetime of the project. The original PEMP included the use of underwater video and land-based surveys to understand disturbance and collision risk for marine mammals and seabirds (Smith 2024; see Chapter 6). The PEMP was updated in 2022 to narrow the focus of the land-based surveys to gathering detailed information on marine birds and mammals just within the array area, following trials of new methods subsequently approved by the regulator, Marine Scotland (Smith 2022). The PEMP was further updated in 2024 following regulatory approval to eliminate the use of land-based surveys (Smith 2024), having shown that there has been no significant disturbance to marine mammals or seabirds (Smith 2022).

The underwater video cameras are directly mounted on the turbines, looking at the rotor-swept area, and are continuously recording but are not illuminated, so they are only effective during daylight. Over the years of deployment, the underwater video recording has generated considerable amounts of footage; Nova Innovation has implemented automated detection of animals to process the videos (Love et al. 2023; Box 2.1).

To date the method has captured underwater images of harbor seals, diving seabirds, and fish in close proximity to the turbines when they are not operating, as well as some of the animals moving away from the turbines when the blades begin rotating (Smith 2021). No animal has ever been observed interacting with any of the moving turbine blades. After consultation with Marine



Scotland, Nova Innovation has transitioned to semi-automated underwater video processing (Smith 2024). Underwater noise generated by turbines in the Shetland Tidal Array was measured in 2023 using drifting hydrophones (Pierpoint et al. 2023). The results demonstrated that acoustic injury to marine mammals is highly unlikely, even after prolonged exposure in proximity to the turbines. Some minor behavioral disturbance may be possible at close range to turbines, reducing the risk of any collisions occurring, but unlikely to result in significant disturbance (Chapter 6).

2.3.3. MARMOK-A-5 WAVE ENERGY CONVERTER

IDOM deployed a single 30-kW floating wave energy converter (WEC), an oscillating water column called MARMOK-A-5, at the offshore Spanish Basque Country test site BiMEP (Figure 2.3). The WEC was deployed twice for a total of 18 months between 2016 and 2019, using the results from the deployments to improve the WEC design. The environmental effects of concern around the WEC that were addressed as part of the ongoing monitoring plan for BiMEP included effects of underwater noise from the generator, EMF emissions from the export cable, and changes in seafloor integrity (Vinagre et al. 2019). Studies on the BiMEP site began in 2012 and continued until after the MARMOK device was removed in 2019 (Bald et al. 2021).

Underwater noise monitoring consisted of six weeks of measurements with a moored hydrophone that recorded sounds for 10 minutes every hour at a fixed location (Felis et al. 2021). In addition, sound was recorded at 17 stations on a single day using the same

BOX 2.1.
AUTOMATED DETECTION OF ANIMALS IN PROXIMITY TO TURBINES USING MACHINE LEARNING

Nova Innovation uses turbine-mounted subsea cameras to monitor nearfield interactions between marine wildlife and turbines in the Shetland Tidal Array, Bluemull Sound, Scotland, United Kingdom. The subsea cameras generate significant quantities of video (1-2 TB per year); the storage, processing, and analysis of which place a significant demand on Nova's resources. To date, the video footage has been analyzed by selecting representative samples for manual review which is an extremely time consuming and resource intensive process.

In 2022, Nova Innovation worked with CGG, a company specializing in earth and geologic systems data and analysis, to explore whether artificial intelligence or machine learning could be used to automate data processing and analysis. A model based on machine learning was developed to automatically filter "unwanted footage" and extract only video files containing marine mammals, diving birds, or fish (i.e., "targets"). Unwanted footage included video files in which any movement was due to moving turbine blades, seaweed fragments and other detritus drifting in currents, or biofouling on the turbines. The model has an accuracy of greater than 94% in distinguishing between video containing marine animal "targets" and "non-targets" (Love et al. 2023). This accuracy will increase as further data are analyzed. In some cases, automated analysis detected targets that were missed when the same footage was analyzed manually. The model has been integrated into a novel, industry-ready workflow that can process approximately 200 videos or 20 hours of footage and produce an automated detection report of the results in approximately 30 minutes. When using a manual approach, it takes approximately 320 person-hours of analysis for 1600 hours of video. By comparison, this automated workflow could analyze 1600 hours of video in 40 hours, resulting in an 87.5% reduction in interpretation time.

The use of machine learning for automated processing provides a subset of data for more focused manual scrutiny and analysis, while reducing the overall size of the dataset requiring storage. This facilitates analysis of a much greater proportion of data and addresses the growing challenges of marine operators' data storage requirements.

hydrophone, and airborne sound was measured at all the locations. Water conductivity, temperature, and depth measurements were collected at each station to support further analyses. EMF was measured using a towed magnetometer along several transects covering the power export cable (Chainho & Bald 2021). Potential effects of the mooring system on seafloor integrity and seabed recovery from cable installation were monitored using a side-scan sonar; underwater videos were recorded by a remotely operated vehicle over the course of two days in 2019 (Muxika et al. 2020).

No EMF emissions were measured from the power export cable (Chainho & Bald 2021) and no changes to seafloor integrity induced by the mooring system and the cable were visible three years after installation (Muxika et al. 2020). The in-water acoustic measurements recorded noise from clanking of chain as part of the mooring lines, with the frequency varying with wave height, as well as the sounds of the generator at intermediate to low frequencies (Felis et al. 2021). Neither interaction was considered to be significant as compared to the ambient EMF, noise conditions, and natural variability (Bald et al. 2021).

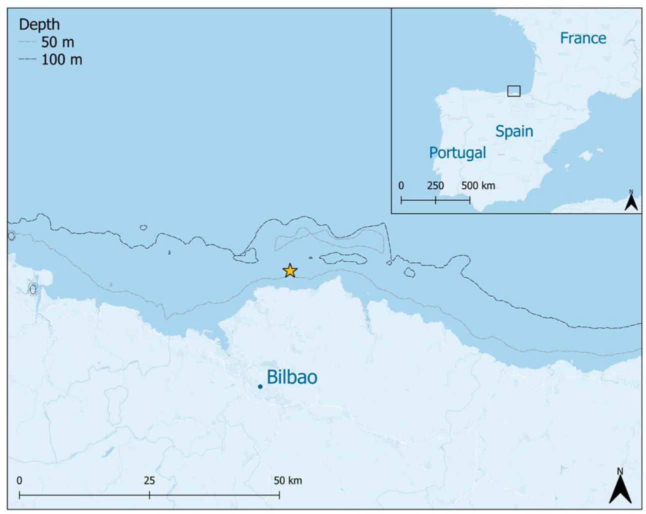


Figure 2.3. Location of IDOM's MARMOK-A-5 wave energy converter at the Biscay Marine Energy Platform in northern Spain (yellow star).

2.3.4.
LYSEKIL WAVE ENERGY TEST SITE

The Lysekil test site is a wave energy test site developed off the west coast of Sweden (Figure 2.4). As of 2024, the site has hosted 13 small WECs for testing. The test site is connected to the power grid by an export cable and was initially consented for testing up to ten devices simultaneously, then updated to allow for 20 devices and two substations. In addition, up to 30 buoys for environmental effects research can be installed. With the deployment of each WEC, studies were carried out with a focus on changes in habitats, effects of underwater noise, and effects of displacement. The studies also sought to develop new monitoring techniques specific to MRE (Bender et al. 2017).

Baseline benthic habitat and artificial reef monitoring began in 2004 then switched to post-deployment monitoring when the first devices were deployed in 2006 and continued for 12 years. Sediment cores were collected to compare infaunal assemblages in the test site area and in a reference area over five years; assemblages differed between sites and years and were most likely influenced by natural processes (Langhamer 2010). The artificial reef effect of the WECs' bottom structures was monitored by scuba diver surveys three years in a row to characterize biofouling assemblages as well as habitat use by mobile species (i.e., fish, crabs, and lobsters); a succession in colonization patterns was observed over time (Langhamer et al. 2009). The site was surveyed again several years later, spanning 12 years between the first and last surveys, highlighting a clear artificial reef effect with increases in diversity and abundance (Bender et al. 2020). The results of the monitoring indicated that the presence and operation of the WECs changed the seafloor habitat very little, and with the addition of holes in the WECs' foundations, created additional habitat for a number of benthic organisms on the site. Lysekil was off limits to harvest; no effects were observed on the abundance and size of decapods during a four-year catch survey using cages (Bender et al. 2021).

In addition, underwater noise was measured with a seabed-mounted hydrophone around two operational WECs for six weeks in 2011 (Haikonen et al. 2013), recording five minutes every 30 minutes. The instrument recorded pulses above ambient noise levels attributed to the WECs that would be audible by local fish and marine mammal species 20 m away from the devices. However, these noise levels were deemed not likely to trigger behavioral responses (Haikonen et al. 2013).

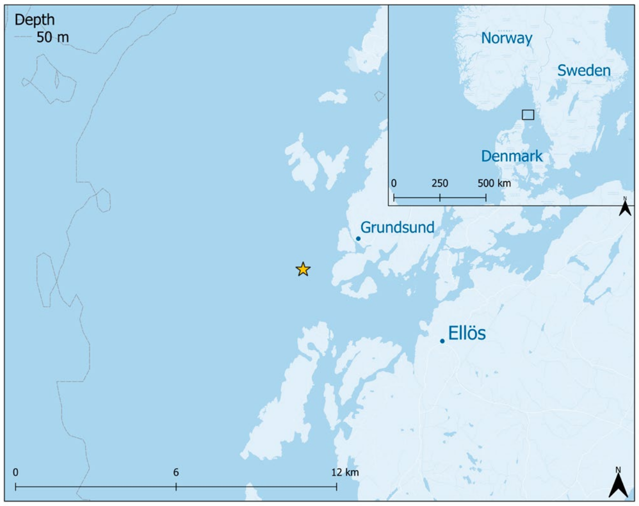


Figure 2.4. Location of the Lysekil Wave Energy Test Site off the west coast of Sweden (yellow star).

2.3.5. IGIUGIG HYDROKINETIC PROJECT

The native village of Igiugig, Alaska partnered with ORPC to install low profile, horizontal, cross-flow riverine RivGen® turbines in the Kvichak River to provide clean power for the village (Thomson et al. 2014) (Figure 2.5). A first test RivGen® device was installed in 2014 and re-deployed in 2015. Results from temporary turbine testing were then incorporated into a Federal Energy Regulatory Commission (FERC) Pilot Project License Application filed by Igiugig Village Council (IVC) in November 2018. In May 2019, FERC issued a 10-year Igiugig Hydrokinetic Pilot Project License allowing for phased deployment and operation of two RivGen® turbines. The RivGen® 2.0 device was deployed in 2019 and the second, RivGen® 2.1, was deployed in 2023, downriver from the first.

The Kvichak River and nearby Bristol Bay tributaries sustain the largest sockeye salmon population in North America. The major concern for regulators and stakeholders during the project permitting and licensing process was the possible collision of migrating salmon adults and smolts with the rotating turbine foils (Priest & Nemeth 2015). In response, IVC and ORPC implemented a fish monitoring plan for the project.

Underwater cameras were installed on the pontoons of the RivGen® to observe fish passage by the turbine (Matzner et al. 2017). Data collected from underwater video cameras around the test turbine deployment in 2015 showed no injuries or behavioral changes to adult salmon during their migration. These preliminary data provided regulators with confidence to complete the licensing process and pursue an adaptive management

approach with IVC and ORPC to address remaining fish passage uncertainties specifically associated with the salmon smolt outmigration.

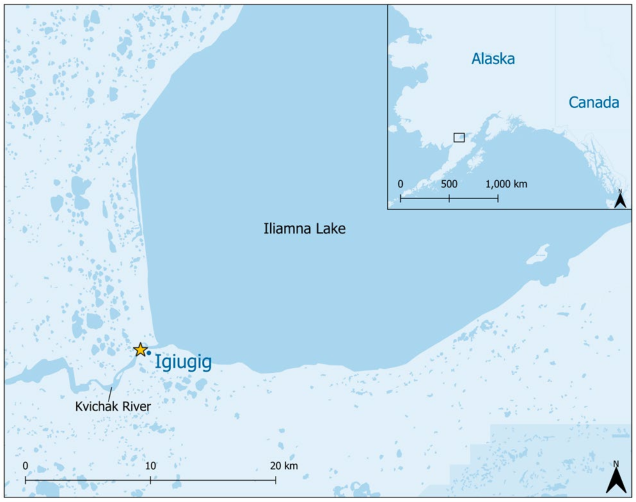


Figure 2.5. Location of ORPC's RivGen® Power System near the village of Igiugig, Alaska, United States (yellow star).

In 2021, IVC and ORPC worked with the University of Alaska Fairbanks to monitor the passage of salmon adults and smolts by the single RivGen® turbine during peak-migration periods (Courtney et al. 2022). The monitoring effort consisted of live video camera monitoring supplemented with on-water visual observations, deployment of an additional in-water camera, and images taken from an aerial drone, coupled with local historical knowledge. Visual observations and camera/drone images identified that the majority of smolt were present in the top meter of the water column, rather than in the deeper waters where the turbine is located. A small proportion of smolts were seen to pass through the RivGen® turbine area, with some showing disorientation as they entered. The monitoring effort did not follow the fish after passage through the turbine but did note a lack of dead fish downstream and no signs of predation by birds or other wildlife. In addition, most smolt out-migrated during hours of complete darkness (00:00 – 04:00); no adult salmon were observed near the turbine. After the 2021 monitoring season, regulators removed the adult salmon monitoring requirements as the potential risk was resolved.

IVC and ORPC continue to monitor and assess project operations during the smolt out-migration. In 2022, the Pacific Northwest National Laboratory completed a side-looking split-bean sonar study as part of the development of a probability of encounter model. Preliminary results from the study indicate that a majority of smolt migrate higher in the water column than the RivGen®.

Ongoing video monitoring continues to assist with growing the knowledge base for fish collision risk. IVC and ORPC continue to opportunistically work with researchers to incorporate experimental studies that are helping to resolve the risk associated with salmon smolt passage during out-migration.

Additionally, although not required by regulators, the sound of the two turbines is being monitored with hydrophones (stationary and drifting) deployed in the river to determine the underwater noise output and to gather data to validate the international specification for measuring sound from an MRE device, developed under the International Electrochemical Committee's Technical Committee for marine energy (TC114) (IEC 2024).

2.4. PATTERNS OF ENVIRONMENTAL EFFECTS STUDIES

The development of MRE around the world is not consistent, with differing numbers of deployments among regions and countries; MRE deployments associated with environmental effects monitoring tend to follow this pattern. For example, the UK has hosted the largest number of deployments and environmental studies of any single country. The presence and operation of the European Marine Energy Centre (EMEC), funded by the European Union and the UK government, helped to boost MRE development and studies (EMEC 2024).

The UK leads in the number of deployed devices with environmental studies (33), followed by Europe (19), and the Americas (22). Australia has also made significant contributions with ten deployed wave energy devices. Most projects worldwide have been conducted at test sites or as pilot demonstration projects, with some contributing to the local or national grids. In addition to EMEC, other test sites in Europe such as BiMEP in Spain and the Wave Energy Test Site (WETS) in the US play a crucial role in facilitating deployments and hosting environmental monitoring studies, as well as developing instrumentation and methods for collecting data around operational MRE devices.

Several MRE projects around the world have commercial offtakers providing power at a scale that is appropriate for their end users, such as the two tidal arrays in Scotland: the MeyGen project in Pentland Firth (four turbines) and the Nova Innovation project in Bluemull Sound in the Shetland Islands (six turbines). Five tidal turbines are also operating in the Eastern Scheldt storm surge barrier in the Netherlands as the Oosterschelde Tidal Power project. Riverine projects in Alaska are providing the level of power needed for commercial development, and the wave energy Eco Wave Power Station is considered to be an operational commercial project in Jaffa, Israel.

Several factors appear to drive the number of assessments and monitoring programs for potential environmental effects, including:

- **Development of MRE projects** – Countries with more MRE development tend to invest in more environmental effects studies.
- **Data availability** – Availability of good data that have been collected for strategic baseline assessments or other uses within the area of a proposed project, help to spur follow up studies.
- **Regulatory processes** – The presence of an established regulatory process in a country influences the level of environmental monitoring required for MRE development, often requiring specific monitoring of interactions of MRE devices with marine animals, habitats, and ecosystem processes.
- **Location of projects** – MRE projects proposed for areas where species of concern are present may be subject to more intense regulatory scrutiny, resulting in more environmental studies.
- **Research capabilities** – The presence of research groups and facilities that focus on environmental effects of MRE in a country contributes to more data collection and analysis.
- **Maritime capabilities** – Access to assets needed for deploying MRE devices and assessments of environmental effects including capable vessels, remote operating vehicles, and trained professionals to operate them, tends to lead to more environmental data collection.
- **Other marine uses** – Planned deployments of MRE devices in areas where other users are active such as fishing, shipping, and marine recreation may influence community opposition, resulting in the need for more intensive environmental assessments.
- **Funding availability** – The availability of funding at strategic and project levels influences the capacity to carry out environmental studies.

2.5.
OUTCOMES OF MRE ENVIRONMENTAL EFFECTS MONITORING

This chapter provides a comprehensive overview of MRE environmental data collection and analysis efforts around the world, and highlights the importance of gathering data related to stressor-receptor interactions to support consenting processes. In particular, this assessment of project studies demonstrates the:

- **Scope of data collection** – Almost 90 projects have been examined, which provides an estimate of the breadth of research in this field. The projects have largely focused on the stressor-receptor interactions previously identified by OES-Environmental and others as crucial to understanding the environmental effects of MRE development (Boehlert & Gill 2010).
- **Monitoring focus for device types** – For the seven stressor-receptor interactions of importance for evaluating MRE effects, each type of device (tidal, wave, riverine, ocean current, OTEC) requires specific areas of focus for monitoring.
- **Methods** – The ability to compare studies from around the world points to the importance of using consistent methodologies for field data collection, numerical models, laboratory studies, and analyses.
- **Regional disparities** – There are significant differences in the development of MRE technologies and environmental studies among regions and countries. Wealthier countries with established test sites tend to support more extensive research and development in the MRE sector.
- **Data sharing and collaboration** – There is growing recognition of the importance of sharing data and collaborating across industry, academia, and other research organizations to advance understanding of environmental effects and to facilitate informed decision-making.

The projects for which environmental effects have been investigated were organized largely around the seven stressor-receptor interactions. Data collection for each interaction provided a unique set of challenges and were addressed with fit for purpose instrumentation and sample collection or modeling efforts. However, there continue to be significant differences among how each interaction is evaluated, from project to project. Tidal stream and riverine projects primarily focus on collecting data to inform collision risk, which remains the most significant concern for consenting (Sparling et al. 2020). Wave energy projects most commonly collect data on underwater noise as concerns about collision are limited for these devices (Copping & Hemery 2020; Cruz et al. 2015). There are few EMF datasets around operational MRE devices; the risk from this interaction is thought to be low for the levels of power carried by MRE cables, as estimated by laboratory and field studies (Gill & Desender 2020; Taormina et al. 2018). Tidal and wave energy project sites were assessed for changes in benthic habitats, with few assessments of pelagic habitat changes. Modeling efforts to assess changes in oceanographic conditions are carried out for both tidal and wave projects, although there are few field measurements that are useful for the validation of the models (Whiting et al. 2023). With few devices and only small arrays in the water, there are few efforts to examine displacement of animals due to the presence or operation of MRE devices (Hemery et al. 2024). Entanglement studies were not found at all.

While OES-Environmental does not attempt to develop or encourage the use of specific instruments or protocols for data collection, it is clear that the range of methods used around the world complicates direct comparisons of outcomes of multiple projects (Hemery et al. 2022). The risk retirement process discussed in Chapter 6 attempts to address this heterogeneity through a series of data transferability envelopes.

Many of the projects with significant environmental data collection have been carried out at established test sites or centers. The use of these test facilities has the potential to accelerate deployments and collect environmental data that are consistent and applicable beyond the site. It is essential that data collected and knowledge gained from environmental monitoring be shared with device and project developers, regulators, advisors, researchers, and other stakeholders to assure that hard-won lessons are not lost and that studies are not unnecessarily repeated. However, sharing data and collective learning depends strongly on all the parties being highly committed to producing open-access data, papers, and reports, and making sure that datasets are archived and made accessible on open access sites.

2.6.
RECOMMENDATIONS FOR ENVIRONMENTAL EFFECTS ASSESSMENT AND MONITORING

This assessment of projects with environmental effects studies has illuminated several deficiencies and challenges for expanding the knowledge base of effects and assuring that high quality comparable data are collected around the world. Several actions could assist with this effort:

- **Baseline assessment** – A comprehensive baseline of biological populations and physical attributes is often helpful in determining ambient conditions. These data should be collected before deployment at prospective commercial-scale project sites. Wherever possible, historical data should be used. Smaller end uses of MRE may require a less extensive baseline assessment as potential effects are expected to be more limited.
- **Existing data on environmental effects** – Comparable data that have been collected at previously consented sites or from research studies should be used where possible to augment data collected on site.
- **Risk identification and assessment** – Potential risks to marine animals, habitats, and ecosystem processes should be identified from prior research, in order to focus data collection and analysis on the highest risks.
- **Gaps analysis and monitoring plans** – Stressor-receptor interactions without sufficient information to determine risk should be identified and used to design post-installation plans.
- **Expert collaboration** – Use of experts in research, offshore operations, and instrumentation can greatly improve the quality and outcomes of monitoring programs.
- **Data use in consenting** – Baseline assessment and post-installation monitoring data should be applied to the consenting process, ensuring data transparency and accessibility through the use of open-source data platforms.
- **Community engagement** – Engaging early on with nearby communities will assist with understanding their values and needs, which will help with the community's acceptance and sense of stewardship for projects, sometimes referred to as "social license".
- **Access to resources** – Making tools and guidance accessible will accelerate processes for consenting and developing monitoring plans, including resources from OES-Environmental, Tethys, and the Offshore Renewables Joint Industry Programme for Ocean Energy (ORJIP 2024).
- **Collaborative approach** – Broad engagement among MRE developers, researchers, supply chain personnel, regulators, advisors, and other stakeholders will assist in the development of sustainable MRE projects and can help to leverage funding to reduce financial burdens on developers.

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Suggested citation:

Copping, A. E and Hemery, L. G. 2024. Progress in Understanding Environmental Effects of Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 8-25). doi:10.2172/2438587

Section B

UPDATING THE STATE OF THE SCIENCE

CHAPTER 3.0
MARINE RENEWABLE ENERGY: STRESSOR-RECEPTOR INTERACTIONS

3.0

Marine Renewable Energy: Stressor–Receptor Interactions

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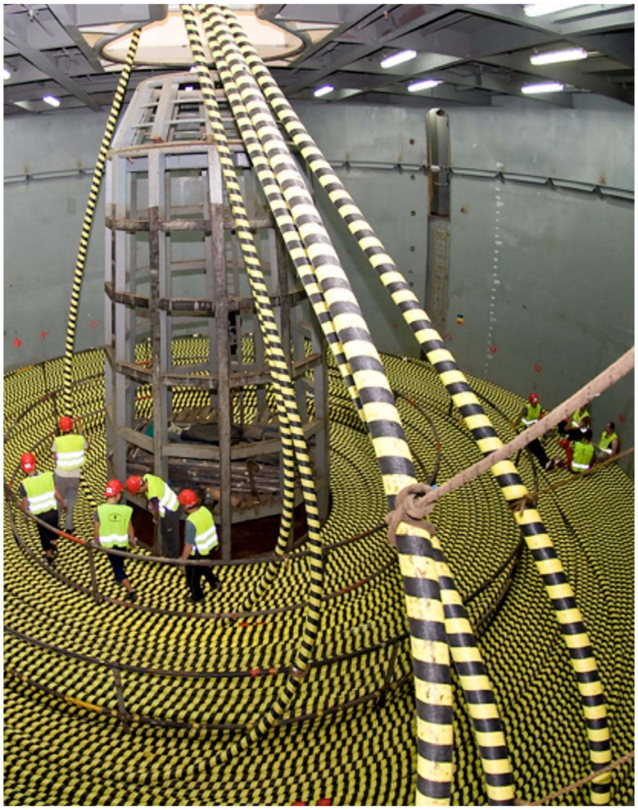
Determining the potential effects of marine renewable energy (MRE) development on the ocean requires consideration of how each component of a tidal, wave, riverine, or other MRE system might affect marine animals, habitats that support marine communities, or processes that make up essential oceanographic and ecological systems.



Researchers around the world have been assessing the potential effects of MRE deployments and operations using a variety of instruments, models, analytical methods, and approaches. The most common approach, and the one followed throughout this report, is the framework of stressor–receptor interactions (Boehlert & Gill 2010), where stressors are the components of an MRE device and associated system that may cause stress, injury, or death to a marine animal, habitat, or ecosystem. The receptors are the species, their habitats, and the oceanographic and ecological processes that support them.

At present, only a small number of MRE devices have been deployed, and while commercial development of MRE arrays may present additional stressor-receptor interactions in the future, seven interactions have been recognized as key to understanding the potential effects of MRE development. These stressor-receptor interactions are:

- Risk of collision of marine animals with moving parts of MRE devices, generally associated with tidal, riverine, or ocean current turbines;
- Effects of underwater noise from operational MRE devices on marine animal behavior and essential sensory capabilities;
- Effects of electromagnetic fields (EMFs) from power cables and other portions of energized MRE devices on sensitive marine animals;
- Changes in benthic and pelagic habitats that support marine species;
- Entanglement of large marine animals in mooring lines or draped cables associated with MRE devices;
- Changes in oceanographic systems due to changes in ocean circulation, wave height, energy removal, or sediment transport; and
- Displacement of marine animals from their normal movements or migratory patterns due to the presence of MRE devices.

This chapter provides a succinct background on the state of knowledge of each of these stressor-receptor interactions, as documented in the *2020 State of the Science* report (Copping & Hemery 2020), followed by updates in research, monitoring, and further insights into the stressor-receptor interactions that have been documented since 2020.[1] Most of the existing information on these interactions pertains to tidal or river turbines and wave energy converters (WECs), as these technologies are the most common types of MRE that have been developed and deployed at the moment. Although devices designed to harvest energy from persistent ocean currents at the western sides of ocean basins are being developed, few have been tested in open water and little is known about their potential environmental effects. In addition, early development of systems to harvest energy from thermal and salinity gradients in the ocean is under consideration.

1. Displacement was not reported in the *2020 State of the Science* report; the assessment of this stressor-receptor interaction in this chapter covers all available information on that topic.

Ocean thermal energy conversion (OTEC)—the generation of power from the temperature differential between warm surface ocean water in the tropics and cold deep ocean water—is a technology that has been investigated longer than other MRE technology, yet has not gained commercial traction; it is currently under revived consideration in tropical islands and remote areas. Where applicable, the stressor-receptor interactions associated with OTEC will be discussed. Salinity gradient power is generated from the osmotic pressure differential of freshwater meeting ocean water at river mouths, and is in the early stages of testing, but little is known about potential effects.

3.1. COLLISION RISK FOR MARINE ANIMALS AROUND TURBINES

Authors: Lysel Garavelli, Deborah J. Rose, Andrea E. Copping

Uncertainty around the likelihood of an animal coming into contact with a turbine blade and the consequences of such an event on the individual and the population remains a key barrier to consenting new tidal or riverine energy projects (Figure 3.1.1). Concerns around collision risk have resulted in significant time delays for projects, with some being abandoned (Copping & Hemery 2020). As such, uncertainty around this issue continues to have a significant impact on the sustainable development of the tidal and riverine energy sector. Reducing uncertainty around all aspects of collision risk for key receptor groups (including marine mammals, fish, and diving seabirds), is a priority for strategic environmental research programs and project-level post-consent monitoring.

Several terms are used to describe the potential interactions of marine animals with MRE turbines such as encounter, avoidance, evasion, and collision (Box 3.1.1). The assignment of each term depends on the spatial scale at which an animal interacts with a turbine (Figure 3.1.2). One of the challenges in reducing uncertainty around the potential risk of collision between marine animals and turbines is related to the ability to gather useful data about each type of interaction.

Observations using sensors (e.g., video cameras) around turbines are technically challenging, within the

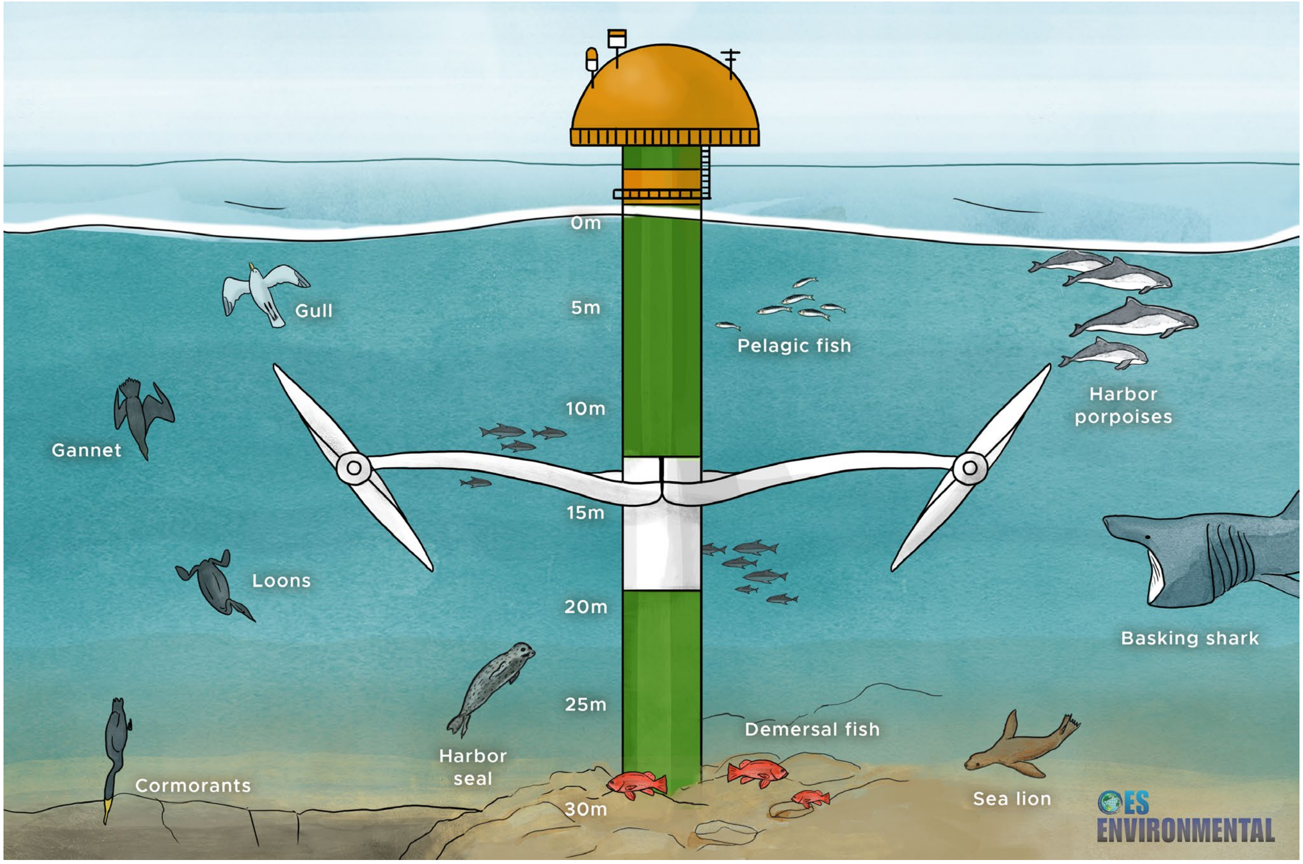


Figure 3.1.1. Schematic of marine animals (seabirds, fish, marine mammals) that can interact with a turbine. (Illustration by Stephanie King)

high-energy, often turbid waters where turbines are typically deployed. Individual animal behavior, sensory capabilities, and learning abilities vary greatly across species and locations of deployment, which, combined with a lack of understanding of the natural behavior of these animals in these environments, result in further uncertainty around the understanding of potential responses to the presence of MRE turbines. There are no appropriate analogs that can represent the interaction of marine animals and turbines (Sparling et al. 2020a), requiring that observations and assessments rely on real-world deployments of turbines at sea or in riverine environments that are accompanied by comprehensive monitoring programs.

In the *2020 State of the Science* report (see Sparling et al. 2020a), general recommendations to better understand collision risk for marine mammals, fish, and seabirds included:

- improving technologies for monitoring and assessing collision risk;
- collecting species-specific data on behavior and presence across seasons and at different sites;
- investigating sublethal injuries after collision events and how these injuries might result in death to the animal;
- understanding how individual losses could be scaled up to population effects; and
- creating array-scale collision risk models (including variability and uncertainty in risk modeling).

BOX 3.1.1.
DEFINITIONS OF TERMS RELATED TO COLLISION RISK

The different ways that animals interact with marine renewable energy turbines are also illustrated in the Marine Energy Adventure: Collision Risk game (see Chapter 7).

- Encounter: when an animal is in proximity of a tidal turbine (= nearfield), at about 1-5 turbine diameters.
- Avoidance: behavior of an animal responding to and moving away from a turbine at a distance greater than 5 turbine diameters.
- Evasion: when an animal changes its behavior to escape contact with a turbine within 5 turbine diameters.
- Collision: when an animal contacts the moving parts (often a blade) of a turbine.

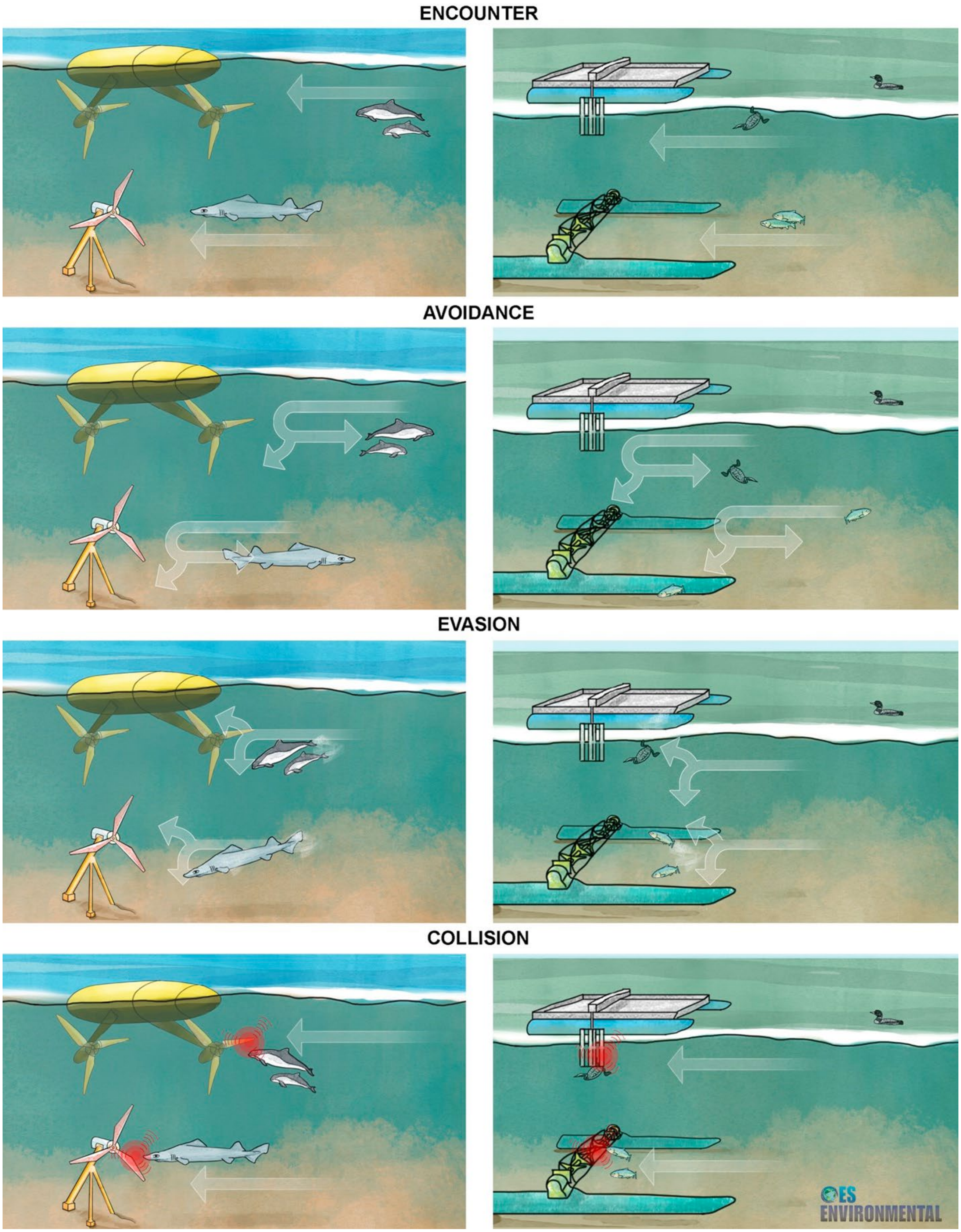


Figure 3.1.2. Interactions between animals and turbines related to collision risk (encounter, avoidance, evasion, collision) at sea (left) and in the river (right). (Illustration by Stephanie King)

3.1.1. ADDITIONAL KNOWLEDGE GAINED SINCE 2020

The current knowledge around collision risk comes from both empirical and modeling studies that examine animal behavior in the vicinity of turbines, such as avoidance and evasion that enable them to avoid harm from collision with turbine blades (Figure 3.1.2). The evidence to date has been from single turbine deployments or small arrays (up to six turbines). Research in recent years has also focused on the probability of animals colliding with turbine blades, using numerical models and probabilistic approaches.

AVOIDANCE AND EVASION

For fish, avoidance behavior is noticed when turbines are operating, and less avoidance behavior is usually observed when the turbine is not operating (Bender et al. 2023; Grippo et al. 2020). In Cobscook Bay, Maine, United States (US), a decrease in fish numbers was observed starting 140 m from the Ocean Renewable Power Company (ORPC) TidGen® tidal turbine (Grippo et al. 2020). Unlike avoidance behavior, evasion behavior of fish at close range to the turbine is challenging to observe due to the technical limitations of monitoring technologies. Evidence of close encounters and evasion by fish around turbine blades has been documented in both laboratory and field settings (Smith 2021; Yoshida et al. 2020, 2022). As part of the environmental monitoring for the Shetland Tidal Array, Bluemull Sound, Shetland, Scotland, United Kingdom, subsea video cameras were deployed on each tidal turbine and 4,049 hours of video footage collected up to March 2020 were analyzed (Smith 2021; see Table 3.1.1). Saithe (*Pollachius virens*; also known as pollock in the US) were frequently observed around the rotating turbines, aggregating in small to large groups. During turbines operations, saithe were never observed to pass through the swept area of the blades and some individuals exhibited evasive behavior when approaching the moving blades. In laboratory conditions, 71% of fish (ray-finned fish *Gnathopogon elongatus*) exhibited evasion behavior near a rotating turbine and fish with slower swimming speeds and those swimming near the bottom of the flume had fewer interactions with the turbine (Yoshida et al. 2022). Müller et al. (2023) observed evasion behavior of fish (juvenile rainbow trout *Oncorhynchus mykiss*) only when the turbine was rotating.

The operation of tidal turbines was also shown to influence the avoidance behavior of marine mammals at several deployments in Scotland. Harbor seals (*Phoca vitulina*) have been observed avoiding a tidal array (four turbines) during turbine operations with the abundance of animals decreasing up to 2 km from the array (Onoufriou et al. 2021). Recent monitoring around four MeyGen tidal turbines shows that harbor porpoises (*Phocoena phocoena*) moved away from the turbines when they were operating, passing to the sides of the device within 10 m, as well as swimming below the rotor swept area (Gillespie et al. 2021; Palmer et al. 2021). At least one harbor porpoise passed through the rotor swept area when the turbine was not operating, but none were seen to pass through the rotor when the turbine blades were rotating (Gillespie et al. 2021). During the environmental monitoring of the Shetland Tidal Array, only 10 individual harbor seals were observed (representing 0.014% of the analyzed footage when considering multiple consecutive occurrences by the same animal), and only at low tidal speeds when the turbine was not operating (Smith 2021).

Seabirds have been observed in video footage collected up to March 2020 from the Shetland Tidal Array environmental monitoring (Smith 2021). Twelve individual European shags (*Phalacrocorax aristotelis*) and five individual black guillemots (*Cepphus grylle*) were observed, when the turbines were not operating, and no physical contact with the blade was observed. The spatial distribution of the seabirds overlapped with the turbines during slack water or current speeds less than 0.8 m/s. Seabird habitat use in tidal development areas has also been assessed through telemetry or observations, with the results used to predict potential interactions with a tidal turbine (Costagliola-Ray et al. 2022; Couto et al. 2022; Isaksson et al. 2021; Johnston et al. 2021. See 3.4.).

COLLISION

Several recent collision risk monitoring studies for fish have focused on detecting direct contact with turbine blades, using different technologies. In Alaska, salmon smolts are of particular concern during their downstream migration. An acoustic camera was used to attempt to detect Pacific salmon (*Oncorhynchus* spp.) smolts and other fishes around the New Energy EnCurrent turbine in the Tanana River Test Site near Nenana, Alaska, US (Staines et al. 2022). The distinction between fish and debris was not possible because fish movement could not be detected. Also in Alaska, potential interactions between Sockeye salmon (*Oncorhynchus nerka*) and the ORPC RivGen® river turbine were assessed with video cameras positioned on the turbine in the Kvichak River (Courtney et al. 2022). Of the 2,374 fish identified in the images, 382 (16%) fish were observed to swim in a disoriented manner. This disoriented behavior was related to the turbulence and flow associated with the presence of the turbine and was rarely observed (2%) when the turbine was not operating. Direct contact between fish and the turbine was observed 36 times (1.5%), at production speed, and the outcomes of collision were unknown because of limited field-of-view. During laboratory experiments, direct contact between fish and turbine blades was observed, only when the turbine was operating, and no injuries were observed (Müller et al. 2023; Yoshida et al. 2020). As of 2024, no collisions between marine fish and tidal turbines have been observed.

So far, field studies assessing the interactions between marine mammals and tidal turbines have not detected any instances of direct contact. The sensory capabilities of marine mammals suggest that collisions with turbine blades will be rare events (Onoufriou et al. 2021). For seabirds, the occurrence of collision with moving structures has never been observed and is likely dependent on their spatial overlap with a turbine in horizontal and vertical dimensions, temporal overlap, and the absence of evasion behavior (Isaksson et al. 2020). Collision risk is expected to be minimal if seabird distribution does not overlap with tidal areas.

NUMERICAL MODELS

The use of numerical models for assessing collision risk is mainly driven by the need to estimate the probabilities of encounter or collision between marine animals and a turbine, to be used to inform regulatory decisions during the consenting process and in post-construction monitoring and management. The purpose of such models is to estimate the likelihood of an encounter or contact (collision) between an animal and a device. The rates of encounter and/or collision depend on several parameters such as the size and location of the device, as well as the animal's behavior. The outcomes are the probabilities of encounter and/or collision. If the survival rate of the animal after a collision is included in the model, the potential effects on the population can be assessed. At the individual scale, two types of models can be used to estimate the interactions between animals and devices: encounter rate models and collision risk models. At the population scale, exposure time (amount of time an animal spends at the depth and in the nearfield of a device) population models can be used (Buenau et al. 2022; see Box 3.1.2).

Models developed to assess collision risk use a large range of parameters as inputs (i.e., data on the technology as well as on the ecology and biology of the animals) and depend strongly on the availability of input data. For fish, field acoustic telemetry detections have been used in a species distribution model (boosted regression tree analysis) to predict the likelihood of animal presence in tidal areas and assess the potential for encounter (Bangley et al. 2022). An alternative analytical approach using acoustic telemetry data estimated the probability of encounter with a tidal device from an ensemble averaged estimate of acoustic detection efficiency (Sanderson et al. 2023a).

Because existing collision risk models do not consider fish behavior, the influence of vertical swimming behavior (direction, speed) on collision rate for silver eels (*Ariosoma mellissii*) was assessed using a coupling between a hydrodynamic model and an agent-based model (Rossington & Benson 2020). The highest collision rate was predicted without vertical migration in the model, highlighting the need to consider realistic animal behavior when modeling collision risk. To estimate probabilities of encounter and the subsequent potential interactions between fish and a turbine, Peraza & Horne (2023) incorporated empirical data of fish distribution and avoidance scenarios in a probability model. Probabilities of encounter and interactions with turbines (i.e., impact) were lowest when avoidance behavior was included. To estimate the probability of collision between marine animals and a turbine, spatial simulations can also be used. A four-dimensional (three dimensions and time) simulation-based approach was developed by Horne et al. (2021) and included flexible parameters for the device and the animal movement. Such a model has been used to estimate the collision probability between a tidal kite and a seal, considering the angle of approach of the animal toward the device, its speed, and its size. The variation of input parameters influenced the collision probability. A similar approach was used to estimate mortality after a collision with a turbine depending on the speed and location of the collision (Horne et al. 2022).

Since 2020, no models have been developed to estimate the collision probabilities of seabirds with a turbine.

PROBABILISTIC APPROACH

Given the challenges associated with collecting data around the likelihood and consequence of collision events and the limitations of numerical models, Copping et al. (2023) developed a framework for organizing data to move toward quantifying the likelihood of sequential events that must take place for a marine animal to approach an operating tidal turbine, collide with a rotating turbine blade, and be harmed. This framework relies on stressor-receptor interactions for tidal turbine blades and the marine animals most likely to encounter them, and outlines a stepwise probabilistic methodology that applies existing knowledge. The framework is based on a "bullseye" approach with concentric circles of probabilities of occurrence, with the "worst-case" outcome (serious injury or death of a marine animal) as the middle circle (Figure 3.1.3).

The probability that a marine animal will suffer a significant injury or death from a collision with a tidal turbine blade is represented by the center red dot (Figure 3.1.3). However, for this outcome to occur, each of the previous steps must result in a positive probability of occurrence, starting with the outer ring of the bullseye (probability of *being present in the water column* and the *vicinity of the turbine*). The probability of a marine animal suffering a deleterious outcome (step 6 – animal collides with rotating turbine blade and step 7 – animal injured or killed), will result only if the animal "successfully" meets the probability of each one of the steps in sequence. For example, a marine mammal, fish, or diving seabird must:

- Be present in the vicinity of the turbine (step1);
- Be at the depth of the turbine (step 2);
- Be present when the turbine is rotating (step 3);
- Not avoid or evade the turbine blades (step 4); and
- Not be small enough to be deflected away from the face of the turbine due to the hydrodynamic forces (step 5).

If every one of these circumstances is satisfied, the animal may enter the rotor swept area, but must encounter a turbine blade that is rotating through the area (step 6), and that collision must occur at sufficient speed on a vulnerable part of the animal's body (likely the head or abdomen) to cause death or an injury from which the animal will not recover (step 7). If any of the steps in the framework presents a near zero probability of occurrence, the overall probability, and therefore the risk of collision, must be considered near zero as well. However, if any step in the process is shown to present a more substantial risk, there is a need to delve into that step in more detail. This framework can also help pinpoint the steps at which a greater risk of collision might be derived, allowing for the direction and amplification of resources to reduce the uncertainty of that step, and potentially apply mitigation.

At this time, it is not possible to quantitatively measure what the probability will be of a marine animal meeting the requirements at each step of the framework; additionally, the probabilities will be dependent

BOX 3.1.2.
DESCRIPTION OF MODELS CURRENTLY USED IN COLLISION RISK STUDIES

Encounter rate model: Analytical model with a similar structure to that of a predator-prey model, with the predator being the blade of a turbine and the prey being the animal (Wilson et al. 2007). Parameters included in an encounter rate model are the volume of water swept by the blades, the size of the prey, the prey density, and the relative swimming speeds of both predator and prey. In an encounter rate model, the turbine blade, viewed from the side, sweeps a certain volume of water in a unit of time that an animal has some probability of occupying. The outcome is the likelihood of encounter between the animal and the turbine blade.

Collision risk model: Based on the Band (2012) model developed to assess the collision risk of birds with wind turbines. The analytical approach of a collision risk model integrates the area covered by the turbine rotor, the size of the animal, its transit time across the plane of the rotor, and the animal behavior and density. Analytical collision risk models are sensitive to assumptions about avoidance rate; however, studies rarely include avoidance or evasion behavior within a model. Spatial simulations are another approach to assess collision risk with the representation of an animal and a device in 3D over time (Rossington & Benson, 2020). Spatial simulations integrate the shape and movement of a device, the animal's behavior, and size.

Exposure time population model: Approaches collision risk from the perspective of populations. This model was developed by Grant et al. (2014) for assessing the collision of diving birds with tidal turbines, but can be applied to other species. It integrates two models: a population model and an exposure time model. The population model estimates the amount of additional mortality caused by collisions that would not decrease the population growth rate. The exposure time model estimates a collision probability from the amount of time animals spend at the depth of the device and the proportion of that depth occupied by the device. The combination of both models estimates the collision risk per unit of time based on existing data for the population size and the individual exposure time. All the collision events are assumed to be fatal, and the animal's behavior is not included.

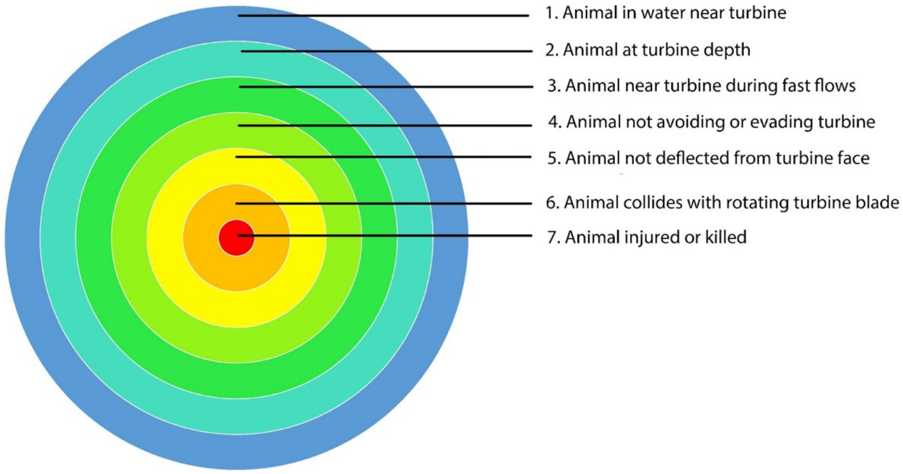


Figure 3.1.3. A conceptual probabilistic framework for organizing data to move toward quantifying the likelihood of collision risk for marine animals and operational tidal energy turbines. The framework outlines a series of sequential steps that must take place, each with an associated probability, for a marine animal to approach an operational turbine, be struck by a turbine blade, and be harmed (i.e., suffer a critical injury or mortality). (Figure from Copping et al. 2023)

on: 1) species characteristics including its behavior and anatomical attributes; and 2) the geometry, size, and rotational speed of the turbine. Although the risk of collision will be specific to each project, location, and health of local species, the likelihood of a serious injury or death to an animal can be estimated using the framework developed by Copping et al. (2023).

3.1.2. STATUS OF RISK RETIREMENT

Although animal movements around and within the vicinity of turbines have been monitored at several tidal and riverine turbine sites over the last decade, there have been no observations of marine mammals or diving seabirds coming into direct contact with turbine blades. Overall, estimating collision risk is challenging due to the difficulty of observing marine animals in the vicinity of a tidal or riverine turbine. Environmental conditions (fast currents, high turbidity), low light, and the low probability of a collision event decrease the opportunity to collect useful nearfield data and subsequently use those data to inform collision risk assessments. Even for small MRE developments, uncertainty around the potential effects of collision risk remains and both research and project-level studies are still needed to increase the understanding of the various parameters that inform collision risk assessments, and the potential consequences on individuals and populations of concern. Numerical models have been used to predict collision rates and estimates of mortality, but the outputs of such models are dependent on the assumptions made about the animals' behavior (e.g., the ability to detect or avoid a turbine) and the potential consequences of animals colliding with turbines.

One step toward better understanding collision risk is the increasing availability of monitoring data around single devices and small arrays (ORJIP Ocean Energy, 2022a; Smith 2021). Increased monitoring data will help inform the probabilistic framework of Copping et al. (2023) and other methods of estimating collision risk, including numerical models. A key element of the potential to increase informed monitoring outcomes has become part of certain environmental consenting requirements and research studies, including collecting large amounts of video data recorded around several deployed devices. These datasets can be leveraged for scientific research around collision risk, before designing expensive field campaigns to collect new videos and other data. Some of these video datasets have been provided by developers for researchers to review and assess risks of collision for fish, marine mammals, or seabirds. The current list of identified video datasets is provided in Table 3.1.1. These datasets are often large and require intensive labor to be analyzed, which is time consuming and costly. Automated processing is therefore needed to analyze these large volumes of datasets, identify marine animals present in the images, and potentially characterize their behavior around a turbine. Love et al. (2023) developed a machine learning algorithm to analyze the underwater video footage obtained around the Shetland Tidal Array (Smith 2024; Table 3.1.1; see Chapter 2). The algorithm accuracy to classify marine animals was 80%, differentiating the animals from

Table 3.1.1. List of existing video datasets recorded during post-installation monitoring of tidal turbines.

Developer	Device	Location	Year	Link to metadata or publication	Animals observed in the datasets
Voith Hydro	HyTide	Fall of Warness, Scotland, United Kingdom	2014	https://tethys.pnnl.gov/project-sites/voith-hytide-emec	Fish, seabird
Nova Innovation	M100, M100-D	Bluemull Sound, Shetland, Scotland	2015-2020; ongoing	https://tethys.pnnl.gov/project-sites/nova-innovation-shetland-tidal-array	Fish, harbor seal, seabird
Simec Atlantis (now SAE Renewables)[2]	Andritz Hydro Hammerfest	Pentland Firth, Scotland	2017	https://tethys.pnnl.gov/project-sites/meygen-tidal-energy-project-phase-i	
Sabella	D10	Fromveur Passage, France	2018, 2019	https://tethys.pnnl.gov/project-sites/sabella-d10-tidal-turbine-ushant-island	Fish
SME Canada	PLAT-I	Grand Passage, Canada	2019	https://tethys.pnnl.gov/project-sites/plat-i-463-tidal-energy	Fish, jellyfish
Ocean Renewable Power Company	RivGen®	Kvichak River, Alaska, United States	2021	https://tethys.pnnl.gov/publications/characterizing-sockeye-salmon-smolt-interactions-hydrokinetic-turbine-kvichak-river	Fish

background or detritus. Such analysis of large video datasets could also be useful for the assessment of nearfield effects such as evasion behavior and collision risk. The use of video cameras for data collection is however only suitable at certain sites and has limitations due to environmental factors (e.g., high turbidity, low light). Other types of data, such as from telemetry, acoustic imaging, and (for vocalizing species) passive acoustic monitoring, can also be leveraged for collision risk research. Several recent studies have collected acoustic data to assess the behavior of fish (Bangley et al. 2022; Bender et al. 2023; Grippo et al. 2020) and marine mammals (Gillespie et al. 2021, 2023; Palmer et al. 2021) around deployed turbines.

Although recent field studies have focused on assessing animals' interactions around turbines (Figure 3.1.4), the low number of deployments, the challenges of collecting nearfield data, and the rarity of nearfield encounters 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 (also see Chapter 6). To move forward on risk retirement for collision, Ocean Energy Systems (OES)-Environmental has developed a Collision Risk Evidence Base listing the key research papers and monitoring reports that define what we understand about the risk of collision and a Collision Risk Guidance Document to evaluate collision risk effects within a general regulatory context.

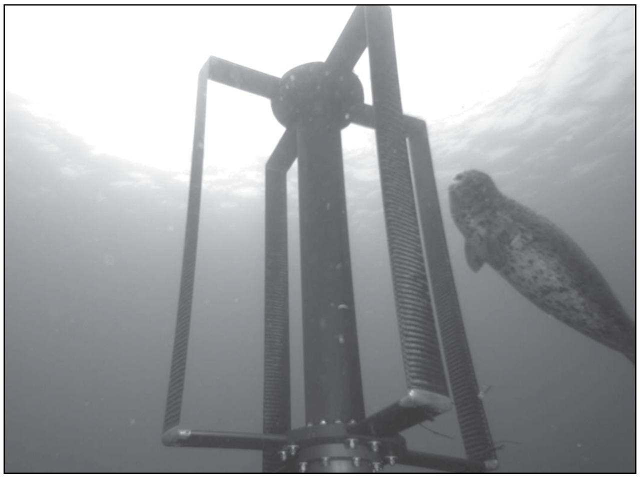


Figure 3.1.4. Photo of a harbor seal (*Phoca vitulina*) swimming around a turbine with stationary rotor at slack tide. Photo courtesy of MarineSitu and Applied Physics Laboratory, University of Washington (left). Photo of a school of saithe/pollock (*Pollachius virens*) swimming around a stationary turbine at the Shetland Tidal Array, Bluemull Sound, Shetland, Scotland, United Kingdom (Smith 2021) (right).

2. No animals were visible on the videos from Simec Atlantis.

3.1.3. RECOMMENDATIONS

Based on existing evidence, there appears to be a very low likelihood of collision events occurring but the potential consequences of even rare events for the animals (e.g., injury or death of an animal) and associated populations remain uncertain. To move forward on resolving these uncertainties and improve our understanding of collision risk, the MRE community (i.e., developers, researchers, regulators, funding agencies, and other stakeholders) needs to agree on high-priority research needs:

- Provide sustainable funding support for targeted research and dissemination of the results;
- Encourage developers through incentives to provide access to their turbines for monitoring, and make public their non-proprietary datasets and metadata on device monitoring studies;
- Focus research efforts on priorities identified by strategic programs; and
- Apply reasonable regulatory frameworks to allow the deployment of new projects in suitable areas to facilitate monitoring and research.

With adequate funding, results from studies on collision risk could be disseminated through direct engagement with regulators, advisors, and stakeholders. A consultative process should also be used to encourage researchers, regulators, and developers to formulate and prioritize important applied research questions that would advance the understanding of collision risk over the next few years.

In the absence of field observations of collision and other forms of measurable data, the use of frameworks for organizing and evaluating the completeness of datasets (Copping et al. 2023) and other methods of setting priorities can play a role in prioritizing information gathering and analysis for consenting. Numerical models are also a key element in interpreting and planning data collection and validation campaigns. Models that inform collision risk require specific input data types that are not necessarily available for all species of concern; collecting these data should become a strategic priority (Wood et al. 2022). Targeted research studies should be developed to fill the data gaps between parameters needed for models and data that are available from empirical studies. The use of integrated instrument platforms including acoustic sensors and cameras is advised to achieve successful monitoring of marine animals and collect relevant data for collision risk. Combining the use of video cameras with active acoustics or echosounders would also be beneficial for species identification. For protected species, the development and use of technologies to determine their presence and assess their behavior in the nearfield is recommended. In many cases, management bodies at the regional, national, or international level will already have assessments of these species that can be leveraged. For example, for managed fish species, it is recommended that MRE researchers work with fisheries agencies to access stock assessments that use repeated protocols for data collection (Xoubanova & Lawrence 2022). These data can then be used to validate models that inform the potential effects of collision risk on populations.

Recommendations for reducing uncertainty around collision risk for marine mammals, fish, and diving seabirds take similar forms; however significant differences in animal behavior, swimming speed, body dimensions, and presence in the water column require different approaches. Recommendations that are common for marine mammals, fish, and seabirds include:

- examining and processing (using artificial intelligence or deep learning methods) all existing video data collected around turbines that have marine mammals, fish, or other animals present, to understand and disseminate the true extent of our current knowledge;
- designing research projects that are geared toward collecting appropriate data for parameterizing and validating numerical models, and informing robust collision risk assessments, thus supporting decision-making processes;
- understanding the different parameters of a turbine that most influence collision risk to encourage the development of lower risk technologies;
- assuring that monitoring is focused on reducing uncertainty around collision risk, is carried out around existing and future turbine deployments, and is designed to answer the important questions for collision risk of fish, marine mammals, and diving seabirds (as appropriately defined by the relevant regulators for key species);
- documenting and disseminating information on the most appropriate set of instruments and methods that will provide accurate observations of collision

- risk, suited to a range of site conditions and species of concern (e.g., Cotter & Staines 2023);
- continuing to update the MRE community on the state of the science on collision risk and encouraging developers to participate in data collection that will lead to robust model development; and
- developing a mitigation and monitoring planning framework for project developers, considering the scale and type of deployment.

In addition, collision risk estimates for marine mammals must consider that relatively few individuals are likely to be present at any time around a tidal turbine. This will necessitate the use of video cameras, as well as high-frequency acoustic cameras and echosounders, to capture images of the rare interactions that may occur or to confirm with greater confidence that encounters are not occurring. Estimates of the population size of marine mammal species known to frequent the areas before tidal energy development occurs are needed to establish a baseline against which to understand how rare encounters might be. This could also help gauge whether tidal turbines are likely to have any impact on animal behavior and local populations. Encounter risk and collision risk models can be useful but the ability to parameterize them, based on low population numbers and sightings (as compared to fish) may be challenging in many areas. Mitigating collision risk for marine mammals might be achieved by scheduling operations based on times when animals are less likely to be present.

Collision risk estimates for fish are more amenable to the collection of data that will drive encounter risk and collision risk models, particularly as many species are likely to aggregate around the structure and associated equipment of a tidal or riverine turbine (Copping et al. 2021a). Understanding the population dynamics and migration timing of large fish populations will help gauge the likelihood of encounter and collision at specific times and seasons. Monitoring fish around turbines will require video cameras, acoustic cameras, and echosounders. With larger populations and a greater likelihood of visualizing fish (compared to marine mammals), shorter monitoring periods will likely suffice to gain sufficient data, provided that seasonal fluctuations in species presence (for migratory fishes) are represented. Similarly, experiments with acoustic telemetry on captive fish released close

to a research turbine could help resolve questions on encounter and collision as well as avoidance and evasion behavior. To mitigate collision risk for fish, the depth at which fish are distributed should be considered when placing the turbine and MRE systems should be adapted to minimize moving parts.

Finally, for seabirds, the risk of collision is expected to change with the type of device, the species of concern, their behavior (e.g., diving depth), and habitat use in the targeted area (ORJIP Ocean Energy, 2022b). The knowledge on collision risk for seabirds is poor and more information is needed to better understand the potential effects of multiple devices. Compared to fish and marine mammals that are always present underwater, seabirds primarily feed within the water column. To mitigate the collision risk of seabirds, minimizing the deployment of a turbine in their feeding habitat should be considered.

3.2.
RISKS TO MARINE ANIMALS FROM UNDERWATER NOISE GENERATED BY MARINE RENEWABLE ENERGY DEVICES

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Marine animals use sound underwater for communication, social interaction, orientation and navigation, foraging, and predation avoidance. Ambient underwater sound environments include natural and biotic contributions from animal vocalizations, breaking waves, sediment movement, and wind or rain at the sea surface. In addition to these natural sounds, marine animals are subject to many sources of anthropogenic noise in the ocean from shipping, construction, surveys, and other marine industries (Duarte et al. 2021). As more MRE device development and installations occur, it is critical to understand how the introduction of these new sources of noise in the marine environment may affect surrounding organisms.

When considering the risks to marine animals that result from the noise produced by any anthropogenic activity, the amplitude, frequency, and directionality of the noise source, as well as propagation losses, prevailing ambient noise, hearing thresholds, and possible behavioral responses need to be considered. Operating MRE devices are generally expected to generate relatively low frequency noise (up to 1000 Hz), though higher frequency noise has been reported more recently for wave and tidal energy converters (Risch et al. 2023). Other anthropogenic noises may cover a much wider range of frequencies (Figure 3.2.1).

There are a range of potential effects of anthropogenic sound on marine animals, either due to the hearing capability of an animal or to other physiological effects (Popper & Hawkins 2019), as shown in Table 3.2.1.

The main receptors considered for understanding the effects of underwater noise are marine mammals, sea turtles, and some fish and invertebrates that have sensory capabilities for detecting changes in the acoustic environment. The effects of underwater noise may be unique to species and individuals within a population (Harding et al. 2019). This can be due to intrinsic characteristics, such as physical attributes, or extrinsic factors, such as previous exposure or the specific habitat in which the sound is produced.

Marine mammals, in particular cetaceans such as whales and harbor porpoises, and pinnipeds such as seals, have traditionally received the most attention and research, in part due to their size, legal protections, cultural value, and public perceptions as charismatic megafauna. In the US, noise thresholds for marine mammals have been set by the National Oceanic and Atmospheric Administration (NOAA) Fisheries (2018) to provide guidance on

Table 3.2.1. Potential effects of anthropogenic sound on marine animals in order of severity (adapted from Popper & Hawkins (2019) and Popper et al. (2023)).

Effect	Description
No obvious responses	Even if an animal detects a sound, it may show no response. This may occur in the presence of a low-level sound. Alternatively, animals may show habituation to repeated sounds.
Behavioral responses	Changes in normal behaviors that could be anything from a small movement (e.g., minor startle response), to movement away from feeding or breeding sites, to changes in migration routes (see Displacement subsection for more information).
Masking	Added sound can reduce the ability of the animal to detect biologically relevant sounds, such as those from potential mates or other conspecifics, predators, or prey.
Hearing threshold shift	Temporary decreased hearing sensitivity leading to decreased detection of biologically relevant sounds such as from oncoming predators or potential mates. **This has not been observed for MRE.**
Physiological changes	Physiological changes, such as changes in hormone levels, may result in increased stress or other effects leading to reduced fitness. **This has not been observed for MRE.**
Physical injury	Physical injury externally or internally, such as a ruptured swim bladder or internal bleeding, that produces immediate or delayed death. **This has not been observed for MRE.**
Death	Instantaneous or delayed mortality. **This has not been observed for MRE.**

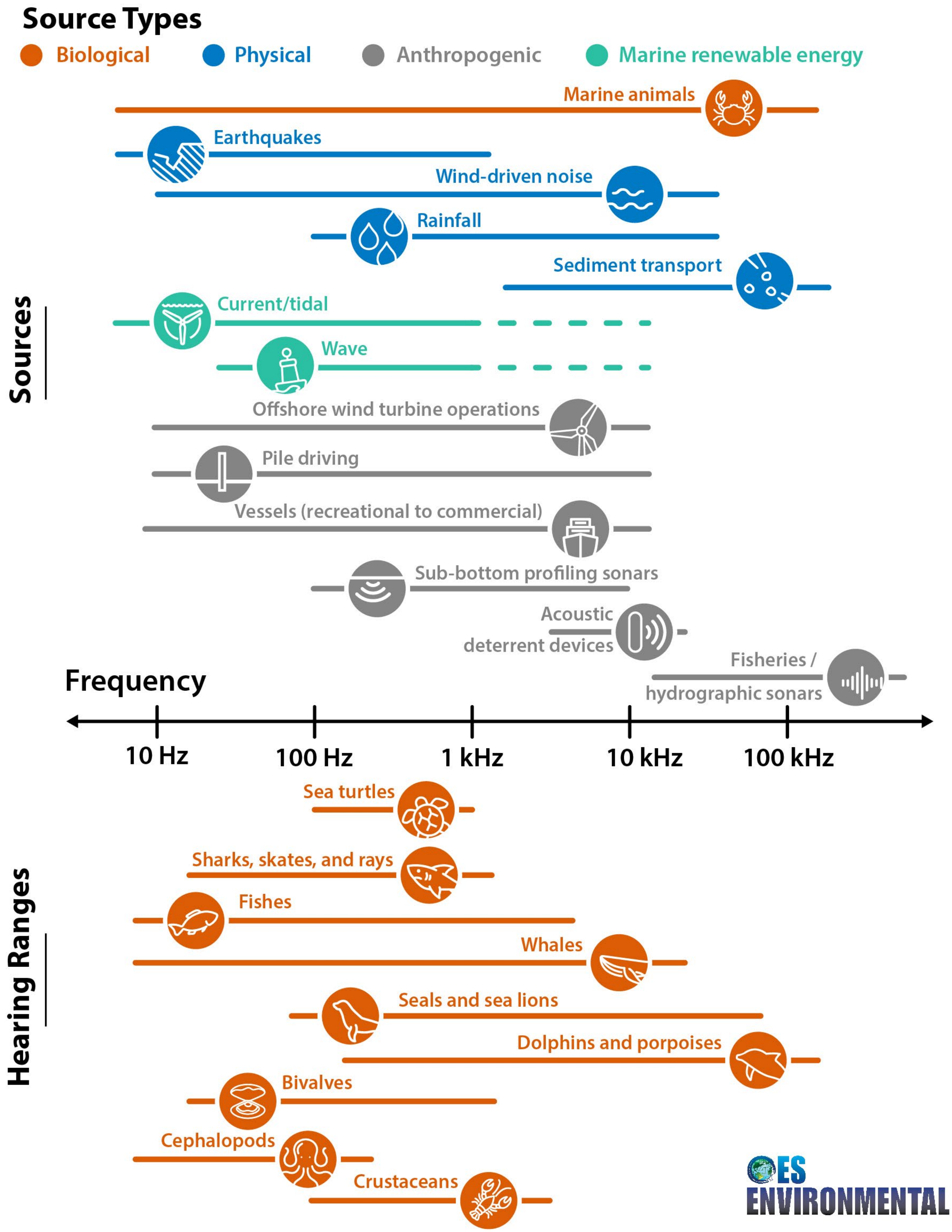


Figure 3.2.1. Sources of sound and their frequencies in the marine environment. Adapted and updated from Polagye & Bassett (2020). (Illustration by Stephanie King)

what levels of underwater noise affect marine mammals temporarily and permanently, as well as on what levels constitute harassment and injury. Several fish species have also been studied extensively (Popper & Hawkins 2019), and interim sound exposure guidelines have been developed for fish (Popper et al. 2014). These guidelines have been used in the US and Europe as representing the best available science (Hawkins et al. 2020). The European Union published its first-ever limits for underwater noise in 2022 under the Marine Strategy Framework Directive (Merchant et al. 2022), adding the requirement that no more than 20% of a specific marine area can be exposed to continuous underwater noise over the course of a year (Borsani et al. 2023). In principle, noise measurements (i.e., operational noise profiles that characterize a device) provided by device developers can be compared to these noise thresholds to evaluate their potential effects on species present at a planned project site, though specific profiles may be considered proprietary and not widely shared.

As of 2020, most studies investigating the underwater noise effects of MRE deployments assessed received sound levels at various distances from operational wave or tidal devices and compared these levels to ambient noise and/or animal hearing sensitivity as a proxy for potential behavioral responses (e.g., Lossent et al. (2018); Risch et al. (2020); Schmitt et al. (2018); Walsh et al. (2017)). Studies have also used "playbacks" of MRE device noise to directly observe animals' behavioral responses (e.g., Hastie et al. (2018, 2021); Robertson et al. (2018); Schramm et al. (2017)). The 2020 State of the Science report (Polagye & Bassett 2020) provides recommendations, including:

- Expanding the evidence base of rigorous, comparable acoustic measurements across a broad range of MRE devices and settings; and
- Establishing a framework for studying animal behavioral consequences of radiated noise from MRE devices.

These recommendations reflected multiple relevant and inter-related themes that inform the general uncertainties around the effects of radiated noise from devices. Technology convergence has not yet occurred among wave or current/tidal devices. When coupled with the differences in underwater noise measurement methodologies, this combination of factors makes direct comparisons between noise emissions from specific devices difficult, complicating a general understanding of the potential effects. However, it is important to emphasize that, even with these measurement challenges, there have been no indications that any effects more serious than behavioral changes in marine animals are likely due to the noise from operational MRE devices.

3.2.1. ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Since the release of the 2020 State of the Science report, many new noise measurement studies have been published, both specific to MRE and on the effects of underwater noise more generally. Several studies have measured sound output and/or potential effects on marine animals at MRE project sites. The findings from each study are available in Table 3.2.2.

Table 3.2.2. Research studies on underwater noise at marine renewable energy project sites since 2020 for wave energy devices, current/tidal energy devices, and ocean thermal energy conversion technologies[3].

WAVE ENERGY		
Reference	**Project / Site**	**Findings**
Buscaino et al. (2019)	Inertial Sea Wave Energy Converter (Pantelleria Island, Italy)	Characterization of ambient underwater noise prior to installation, and characterization of underwater noise produced by devices during installation and operation using a hydrophone deployed at a range of 40 m. Levels of noise measured were higher after installation, especially at frequencies up to 4 kHz and increased with wave heights. Median broadband sound pressure levels at 63 Hz for specific wave heights were 73 dB re 1µPa before, 106 dB re 1 µPa during installation, and 126 dB re 1µPa after.
Bald et al. (2022); Felis et al. (2020, 2021); Madrid et al. (2023)	Wave Energy in Southern Europe (WESE) Project: IDOM-Oceantec MARMOK-A-5 (Biscay Marine Energy Platform [BiMEP] and Mutriku Wave Power Plant, Spain)	Noise was recorded at the MARMOK A-5 device installed at BiMEP and the Mutriku Power Plant. In general, the contribution of the device to the surrounding environment was not significant, producing measurable sound from 40-120 Hz that exceeded ambient noise by up to 14 dB at 100 m, though this declined to 6 dB as significant wave height increased. Noise propagation from a hypothetical array of 80 devices was modeled using a geometric loss model, resulting in a maximum difference of 50 dB re 1 µPa when compared to a single device, and an area of disturbance in a 0.28 km radius around each device.
Raghukumar et al. (2022, 2023)	CalWave (California, United States [US])	The NoiseSpotter® was developed by Integral Consulting, Inc. and used to characterize the CalWave xWave™ WEC. The NoiseSpotter® was deployed at various distances, measuring acoustic pressure as well as particle velocity from 50 Hz to 3 kHz. During operation, sound levels around 95 dB re 1µPa were measured and linked to mechanical operations. In the context of the ambient soundscape, the noise from the wave energy converter was found to be insignificant.
Harding et al. (2023)	PacWave South (Oregon, US)	The effect of noise from a hypothetical wave farm (28 devices) was modeled for the PacWave South test site using ParAcousti, an open-source hydroacoustic propagation modeling tool. A metric—effective signal level—was developed to capture sound propagation, ambient noise, and hearing thresholds for marine species. The model results show many combinations where the hypothetical underwater noise generated by the wave farm was detectable in the study area, though with significant variation based on each set of model inputs, including some unlikely scenarios. The tool can be used to predict potential effects of anthropogenic noise on marine mammals across a variety of settings.

CURRENT/TIDAL ENERGY

Reference	Project / Site	Findings
Rosli et al. (2020)	HydroSpinna (Newcastle University, United Kingdom [UK])	Radiated noise levels from a scale Hydro-Spinna current turbine were measured in a lab test at Newcastle University. The results were extrapolated using models for several sizes of full scale devices and compared to fish reaction levels to noise from the International Council for the Exploration of the Sea (ICES, 1995). For the optimal designs, the turbine noise was found to be lower than the fish reaction threshold, indicating that emitted noise would only exceed the threshold if the device was operating incorrectly.
Haxel et al. (2022)	University of New Hampshire (UNH) Tidal Deployment Platform (New Hampshire, US)	Hydrophones were used to characterize the sound produced by a tidal turbine installed at the UNH Living Bridge. Noise produced by the turbine was not detectable relative to the ambient noise, which was high due to the urban environment and nearly continuous vessel traffic in the area.
Risch et al. (2023)	MeyGen (Scotland, UK)	This study measured noise levels from two tidal turbines deployed at the MeyGen site in the Pentland Firth, a 1.5 MW Atlantis AR1500 and a 1.5MW Andritz AHH1500, using drifting hydrophones and a three-dimensional COMSOL Multiphysics model to derive the source levels. The highest noise levels were between 50 Hz and 1 kHz, with the Andritz turbine generating lower amplitude sound. The current array with four turbines is likely detectable by harbor seals across a 0.2 km2 radius, and scenarios modeling noise propagation for a 30-turbine array of each turbine type suggest a 0.8 km2 radius for the Atlantis turbine and a 0.3 km2 radius for the Andritz turbine.

OCEAN THERMAL ENERGY CONVERSION (OTEC)[3]

Reference	Project / Site	Findings
Auvray et al. (2015)	Planned OTEC power plant on Martinique Island (France)	A model was used to estimate the noise radiated from the proposed OTEC device, propagating the noise from the pumps and turbines to the cold-water pipe. The sound pressure levels were compared to the Sound Exposure Levels for marine mammals (Southall et al. 2007) present at the project site and the nearby Agoa Sanctuary, but the findings were not reported.
Devault and Péné-Annette (2017)	Planned OTEC power plant on Martinique Island (France)	Operational noise was included as a potential effect for the proposed project. Noise levels generated by floating OTEC would be similar to the noise of a slow cargo ship (45-89 Hz), which could be audible to marine mammals but not above injury levels, though construction noise would likely be higher. Effects on dolphins in the close vicinity of the plant would need to be further investigated.
Rahman et al. (2022)	N/A	Multiple renewable energy devices were reviewed to compare their environmental impact. Underwater noise from OTEC was rated a level 3 out of 5 (moderate) for intensity of impact for both installation and operation, though no additional studies or direct measurements were done.

3. Note that a few documents for OTEC are included from prior to 2020 as these were not explicitly considered in the *2020 State of the Science* report.

MEASURING AND MODELING UNDERWATER NOISE

In addition to project studies, several reviews of the state of knowledge for measuring and modeling underwater noise have been published.

Popper et al. (2023) reviewed the acoustic effects of MRE devices on fish and aquatic invertebrates. They find that MRE devices most frequently produce low amplitude, discrete-frequency tonal sounds with harmonics. They also assert that as the MRE industry advances and designs begin to converge, sound radiated from operational devices will become more predictable and easier to characterize, lowering regulator concerns about uncertainty. Also, as the industry progresses, more devices will be deployed, tested, and acoustically characterized, providing additional data to inform decision making. However, they note that substrate vibration from MRE devices that are well coupled to the seafloor (e.g., piles or devices with a large seabed footprint) or devices that emit substantial low-frequency vibrational energy near the seabed could be unpredictable due to variations in substrate composition (e.g., Hawkins et al. 2021).

The existing regulatory frameworks for evaluating acoustic effects of MRE on marine animals rely heavily on sound pressure measurements, prioritizing hydrophones as the critical technology path for characterizing underwater noise. However, in addition to understanding the effects of sound pressure from MRE on marine mammals, new research characterizing the acoustic particle motion component of MRE sounds may also help inform potential effects of underwater noise (Nedelec et al. 2016) for fish and invertebrates that are not sensitive to sound pressure (Popper & Hawkins 2018) (Figure 3.2.2). It is critical to note that in situ

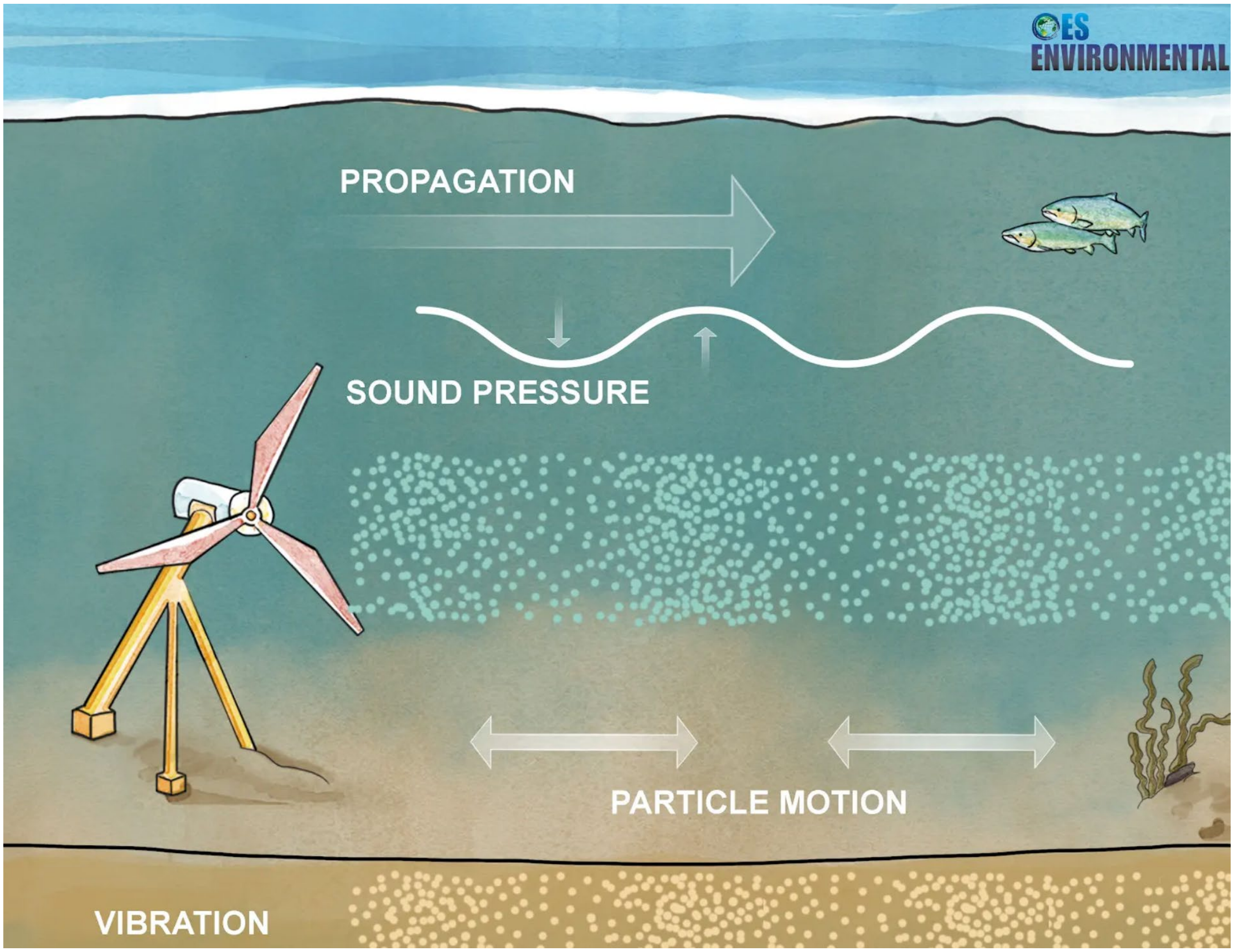


Figure 3.2.2. Underwater noise, particle motion, and vibration as potential stressors, adapted from Hawkins (2022) and Svendsen et al. (2022). A marine renewable energy (MRE) converter can radiate sound energy into the water and vibrations into the seabed. The particle motion component of the sound energy oscillates particles in the seawater back and forth as acoustic pressure propagates away from the device. Similarly, substrate vibration from the MRE converter propagates along and through the seabed away from the device. (Illustration by Stephanie King)

vector measurements of particle motion are more complex than scalar sound pressure measurements and require sophisticated instrumentation that are rarer than simple omni-directional hydrophones. In addition, unlike hydrophones, there is limited understanding of specific considerations required to collect useful data from vector sensors in energetic waves and currents. Therefore, it may be more effective to calculate acoustic particle velocities from sound pressure levels measured by hydrophones where bathymetric complexity allows. Nedelec et al. (2021) provide a best practice guide for measurement of acoustic particle motion, including equipment options and how to determine if particle motion measurements are recommended for biological applications or if it can be calculated from sound pressure. Effects of acoustic particle motion disturbance on fish and invertebrates are poorly understood and require significantly more research.

Buenau et al. (2022) reviewed modeling approaches for underwater noise. Underwater noise modeling is a well-established field, though only a few models are MRE-specific. They found no studies that modeled nearfield noise (10s of meters) from specific devices, or that allowed for environmental complexity (e.g., sea surface or seabed roughness). They also note that modeling effects of underwater noise on marine animals depends on key assumptions about impacts on behavior or vital signs and requires significant baseline data inputs.

van Geel et al. (2022) reviewed existing methods, metrics, and standards for monitoring underwater noise, focused on long-term monitoring for baseline studies and site characterization. They note that choices of metrics and analysis depend on specific research questions, and that full bandwidth of the source noise and, at minimum, the main frequency content of the signal across various relevant time periods, should be captured when possible.

The Helsinki Commission (2021) developed guidelines for monitoring continuous noise for the Baltic Sea, recommending sampling procedures and equipment to ensure consistent measurements, in particular for low-frequency anthropogenic noise (10 Hz to 20 kHz). They suggest selecting a frequency bandwidth between 20 Hz and 20 kHz and a sampling rate at least 2.5 times higher than the bandwidth of interest, as well as providing additional information on device setup, calibration, data processing, and reporting. These guidelines may be required in certain jurisdictions, while the existing international specifications may be most appropriate internationally.

NEW FRAMEWORKS

New frameworks have been developed that may be relevant to underwater noise effects for MRE, although none were prepared for, nor specific to, MRE.

Verling et al. (2021) developed a risk-based approach to assessment and monitoring aligned with the Marine Strategy Framework Directive's goal of achieving Good Environmental Status in European Waters. They applied the approach to the risks associated with continuous underwater noise from shipping on cetaceans. The risk-based approach is demonstrated at different spatial scales and for different levels of data availability.

Ruppel et al. (2022) developed a tiered framework to categorize active underwater acoustics for regulatory purposes in the US, focusing on marine mammals. The framework includes assessment of several key factors, including audibility of the frequency for marine animals, received sound pressure levels less than 160 dB re 1µPa, the sound power level (radiated power), and degree of exposure. While not explicitly discussed, operation of MRE devices that radiate noise would fall under Tier 4 along with other oceanographic research devices, which are considered de minimus sources and are unlikely to harm marine mammals. They recommend that Tier 4 sources be exempt from most formal regulatory review and that a survey-by-survey review is unnecessary for single or multiple sources.

Southall et al. (2023) proposed a framework for assessing effects of anthropogenic noise on marine mammals to include population vulnerability and an exposure index in an ecological, risk-based framework, replacing the use of simple sound thresholds. The examples used in the paper are primarily for pile-driving installation of offshore wind farms, but the framework itself is intended to be used for various operational scenarios that include MRE.

TAXA-SPECIFIC STUDIES

The knowledge base on underwater noise effects from MRE would benefit from studies that do not explicitly include measurements around MRE devices, but instead focus on better understanding the effects of underwater noise, in general, on receptors of concern. This section summarizes a few studies that may be helpful for MRE.

Mickle & Higgs (2022) conducted a review of hearing ability of elasmobranchs, including their attraction and avoidance responses to underwater noise. Elasmobranchs do not have a swim bladder and specialized hearing structures, and as such only detect particle motion. The known hearing abilities of sharks, rays, and skates studied to date range from 25 to 1500 Hz. Sharks seem attracted to irregularly and rapidly pulsed sounds along broad-band frequencies that lacked a sudden increase in intensity, but tend to respond by avoidance to sudden increases in sound levels. (See Chapter 10)

Xoubanova & Lawrence (2022) conducted a literature review and consulted stakeholders to develop an evidence map for strategic fish and fisheries research. Their review includes a section on underwater noise evidence gaps, noting that there remains uncertainty in understanding behavioral responses of fish, effects of particle motion, and technological approaches to mitigation.

Solé et al. (2023) reviewed the knowledge on effects of underwater noise on a wide variety of marine invertebrates (protozoans, cnidarians, ctenophores, flat worms, annelids, mollusks, arrow worms, tunicates, and crustaceans) including study techniques, receptor systems of various invertebrates, acoustic sensitivities, and sound generation on both adults and early life stages at the individual and population levels. They found that biological mechanisms of sound reception and generation are not well described for many invertebrate species, and that adaptation to long-term noise exposure is unlikely due to short life spans for many species. Characterization of existing ambient noise is needed to distinguish the effects of a particular sound, and the interactions between multiple stressors need to be considered when assessing the effects of noise.

Olivier et al. (2023) developed a laboratory tank system to measure the effects of underwater noise on larval stages of marine invertebrates. The device primarily simulates pile-driving and drilling, which produce much higher levels of noise, and as such is less applicable for studying the effects of operational MRE devices.

Zang et al. (2023) reviewed underwater sound assessments for fish to identify knowledge gaps, and utilized a case study of traffic sounds from a floating bridge on tidal waters on migrating steelhead smolts in Washington, US, as an example of best practices for noise assessments. Using the case study, they suggested that even when sound pressure and particle motion levels were below the NOAA Fisheries thresholds identified through lab studies (National Marine Fisheries Service, 2018), there was potential for behavioral changes that could negatively affect migrating fish species in the marine environment. They suggest that this case study has implications for MRE devices due to the similar water depth, complex bathymetry, and confined areas in which MRE devices are likely to be installed.

3.2.2.
STATUS OF RISK RETIREMENT

OES-Environmental has developed an Underwater Noise Evidence Base listing the key research papers and monitoring reports that define what we understand about the risks from operational underwater noise from MRE devices and an Underwater Noise Guidance Document to evaluate the risk within a regulatory context.

The evidence base to date suggests that the effects of underwater noise from small-scale MRE developments are limited. Underwater noise measurements from operational MRE devices show that noise levels generally fall below those likely to cause injury or harm to marine mammals and fish, and that observed behavioral changes are unlikely to be attributed solely to noise from MRE devices. Overall, the scientific community has reached a general consensus that underwater noise from operational devices within small-scale MRE developments does not pose a risk to marine animals and can be retired for small numbers of devices (one to six devices) (Copping et al. 2019; Copping et al. 2020; ORJIP Ocean Energy 2022b; Polagye & Bassett 2020). However, this does not suggest that research on this topic has been discontinued or is no longer necessary, as evidenced by the studies

described in the previous section. The International Electrotechnical Commission Technical Committee (IEC TC) 114 published an international consensus Technical Specification (62600-40) for characterizing radiated noise near MRE devices, which provides protocols for sound measurements to enable consistent data collection and allow for comparison across MRE developments. This specification is now in the process of being updated based on feedback from its use to date. Updates are likely to be relatively minor and emphasize adjustments to deployment strategies. In the US, guidance thresholds for underwater noise exist for marine mammals (National Marine Fisheries Service, 2018) and fish (Popper et al. 2014). Research studies internationally are ongoing to assess the potential effects on new species of concern and various underwater soundscapes (e.g., Triton, Safe-Wave). Despite the growing consensus in the scientific community, regulators remain concerned about the potential effects of underwater noise radiated by MRE devices, and efforts to establish key research priorities for aspects that are not well understood are ongoing (e.g., NOAA's Ocean Noise Strategy, Jomopans (Kinneging 2023), Joint Action Underwater Noise in the Marine Environment).

3.2.3. RECOMMENDATIONS

While progress has been made toward the recommendations from the *2020 State of the Science* report through the characterization of operational MRE devices and efforts to understand effects on animal behavior, significant knowledge gaps still exist. In fact, the recommendations of Polagye & Bassett (2020) remain top priorities. The following additional recommendations will help advance the state of knowledge around underwater noise and enable forward progress of the MRE industry:

- Each new MRE device design should be characterized, ideally using methodology consistent with the IEC TC 114 Technical Specification (62600-40). Measurements to establish the radiated noise signature of each device under different operating conditions are needed. While not part of the Technical Specification, comparisons of noise measurements to thresholds for key species can inform regulatory approaches for specific devices.
- Noise monitoring of operational devices can provide additional benefits, even if not required for consenting. Monitoring noise produced by MRE devices may provide an alternative method for assessing the engineering health of systems, with damaged or malfunctioning systems producing unanticipated sounds (Polagye et al. 2017; Walsh et al. 2015, 2017).

In addition to these recommendations, several research needs have been identified related to underwater noise. Resolution of these knowledge gaps is not likely needed for consenting processes to move forward for MRE, but rather to inform research directions for the broader research community, to address potential aggregated effects of offshore renewables as larger buildouts occur. A better understanding of the links between underwater noise exposure (including sound pressure, particle motion, and substrate vibration) and effects on fish and invertebrates is needed (Popper et al. 2023). Little is known about particle motion and substrate vibration effects on fishes and even less for invertebrates. Studies are also needed on sensory capabilities, including those related to particle motion and substrate vibration that help progress toward a better understanding of meaningful thresholds for disturbance (from the animal's perspective, e.g., masking) with respect to behavioral and physiological responses. Building on existing research (Nedelec et al. 2021), there is a need to characterize and describe conditions where sound pressure measurements are sufficient to calculate particle motion and infer effects on sensitive species. Measurements or calculations to characterize particle motion from MRE devices at project sites should be considered a value-added proposition of lesser importance than sound pressure measurements with hydrophones. More research is needed on effects of operational underwater noise from MRE for sea turtles. This may be an emerging area of research as interest increases in siting MRE projects in subtropical and tropical areas frequented by sea turtles.

3.3.
ELECTROMAGNETIC FIELD EFFECTS FROM POWER CABLES AND MARINE RENEWABLE ENERGY DEVICES

Author: Hayley Farr

As the MRE industry expands around the world, the prevalence of EMFs emitted by subsea power cables and other project infrastructure in the oceans will increase. Based on the knowledge to date, MRE-related EMF effects on marine animals are likely weak for single devices or small arrays; however, substantial uncertainties remain and research is ongoing as more MRE projects are planned and deployed.

EMFs occur naturally in the environment and consist of electric fields (E-fields), measured in volts per meter (V/m), and magnetic fields (B-fields[4]), measured in Tesla (T). The primary source of B-fields is the geomagnetic field, which varies between ~25 μT at the equator to ~65 μT at the poles[5]. In the marine environment, the movement of water or animals through the geomagnetic field creates motion-induced electric fields (iE-fields). Marine animals also produce very low-frequency bioelectric fields that some species can detect. Natural E- and B-fields provide important cues to electro-receptive and magneto-receptive species and the addition of anthropogenic fields may mask or modify these existing fields (Gill et al. 2014).

The primary sources of anthropogenic EMFs associated with MRE systems are the subsea power cables used to transmit the electricity produced to shore, which are either high voltage alternating current (AC) or direct current (DC). Within a cable, the B-field propagates perpendicular to the flow of electrical current along the cable axis, dissipating with distance, while the E-field is fully contained by shielding and grounding (Figure 3.3.1). The characteristics and

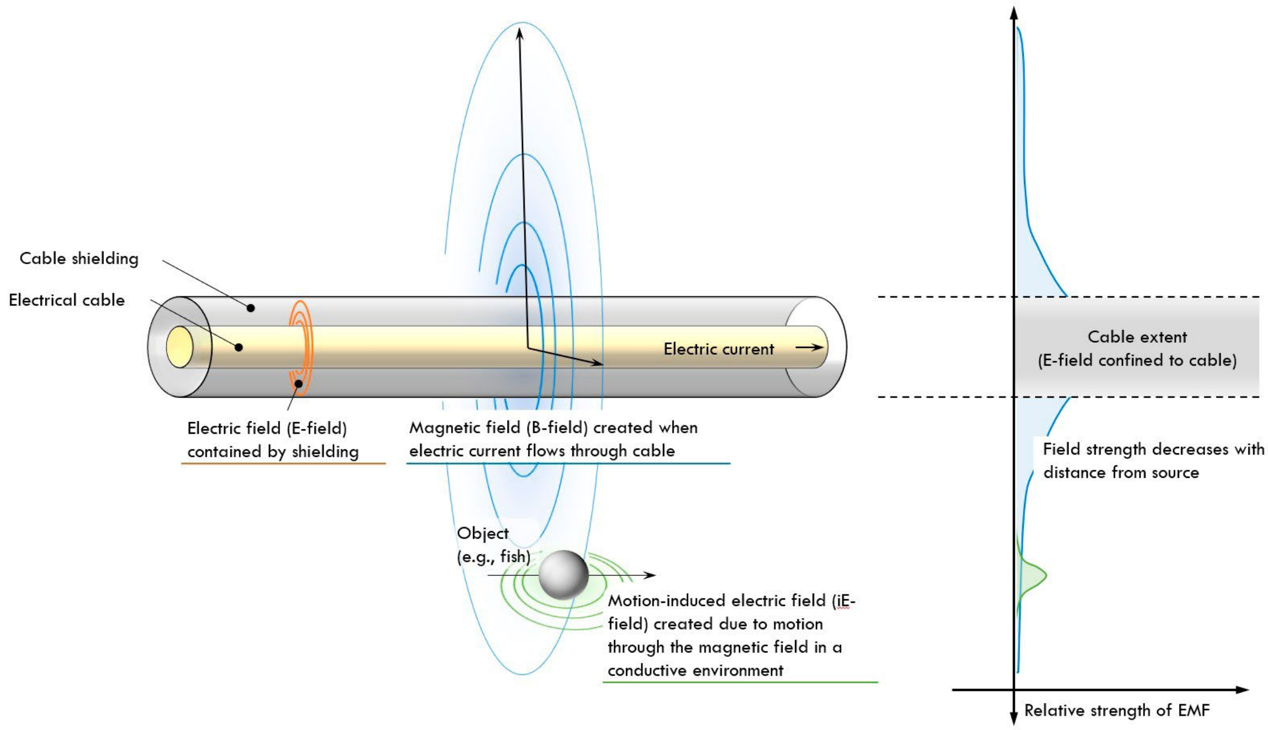


Figure 3.3.1. Depiction of an electromagnetic field (EMF) from an industry standard electrical cable (left) and relative field strength (right) from a snapshot in time. The electric field (orange) is contained by the cable shielding. The magnetic field (blue) is produced by both alternating current (AC) and direct current (DC) cables. A motionally-induced electric field (green) is created as an object or water moves through the geomagnetic field or the magnetic field from a subsea cable. The figure does not show an induced electric field that would be created around an AC cable due to the rotating magnetic field. (Courtesy of Mark Severy)

4. B-field is the accepted nomenclature for the magnetic field. It is technically termed the magnetic flux density. The B-field is easily measured (in Tesla) and considers the permeability of the medium.
5. *https://www.ncei.noaa.gov/products/geomagnetic-data*

strength of EMFs emitted from these cables depend on the cable design, number of cables, type of current (AC or DC), power transmitted, local fields, and other environmental factors.

DC cables generate static B-fields, while AC cables, which have been used more commonly in MRE and offshore wind developments to date, generate B-fields that vary over time. The movement of water or animals through these B-fields generates secondary iE-fields in the environment outside of the cable (Figure 3.3.1); AC cables also produce iE-fields due to the rotating nature of their B-fields (not shown).

In general, the stronger the electrical current, the stronger the emitted B- and iE-fields. The strength of B-fields associated with MRE subsea cables can range from 10s of nT to a few mT, while E-fields can range from 1 to 100 μV/cm, which is similar to the bioelectric fields emitted by prey species (Taormina et al. 2018; Gill & Desender 2020). Cable burial can create additional distance between the strongest field intensities at the cable's surface and most marine animals living on or near the seafloor, but B- and iE-fields in the water column will be present and may be detected by marine species.

Other sources of EMFs include the MRE devices themselves, offshore substations and transformers, and the dynamic inter-array cables that connect devices to one another and to a substation. As more floating MRE projects are deployed, more pelagic species may be exposed to EMFs of varying intensities in the water column. Each cable connecting a device to the seafloor will carry less energy than the export cable running along the seabed to shore. However, there is little research on EMFs from cables in the water column.

Many marine species from diverse taxonomic groups can sense and respond to E- and/or B-fields and may encounter EMFs from MRE developments (Figure 3.3.2). The groups that are the focus of most EMF effects research include certain species of bony fish (teleosts and chondrosteans), crustaceans (crabs, lobsters, and prawns), elasmobranchs (sharks, skates, and rays), mollusks (snails, bivalves, cephalopods), cetaceans (whales and dolphins), and sea turtles. The sensory capabilities, biological relevance, and effects

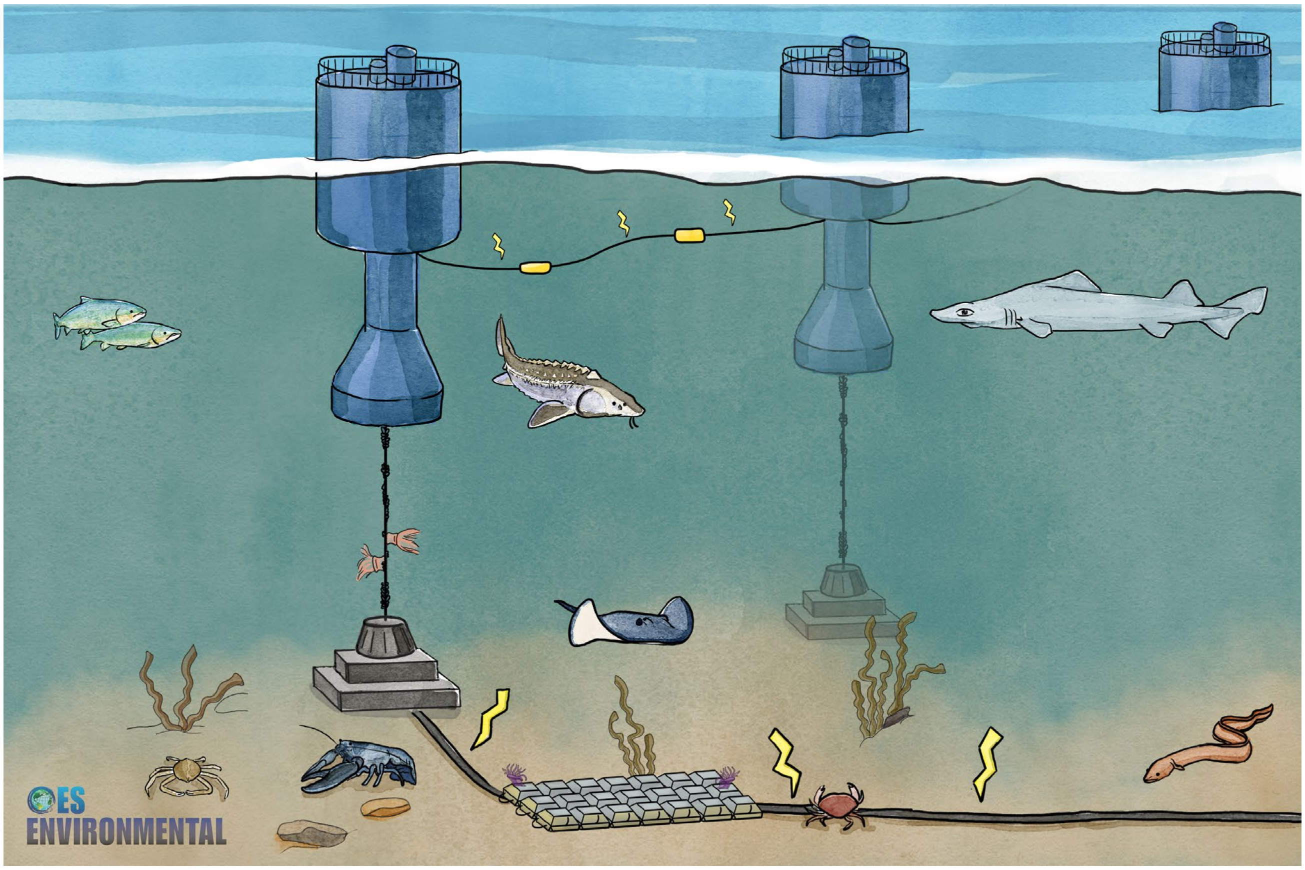
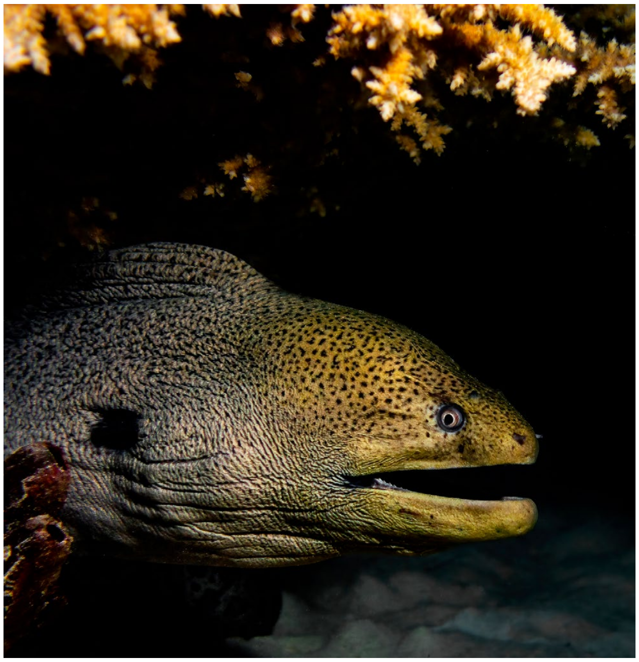


Figure 3.3.2. Illustration of some of the marine species likely to encounter electromagnetic fields emitted by subsea power cables associated with marine renewable energy devices. (Illustration by Stephanie King)



of EMFs vary across species and over different life stages (Nyqvist et al. 2020).

The *2020 State of the Science* report (Copping & Hemery 2020) focused on whether an effect or response recorded in a study can be considered an impact. Research has shown measurable behavioral, physiological, developmental, and genetic effects and responses to relatively high levels of E- and/or B-fields on a small number of individual species, but these effects are not evident at the EMF intensities associated with current small-scale MRE (Gill & Desender 2020).

To fill the remaining knowledge gaps around MRE and EMFs, the *2020 State of the Science* report (Gill & Desender 2020) recommended further efforts toward:

- Developing affordable methods and equipment to simultaneously measure E- and B-fields with the necessary sensitivity and precision for comparability;
- Validating existing models with EMF measurements from deployed MRE devices and power transmission cables;
- Conducting laboratory studies of species response to EMFs at different intensities and durations to determine the thresholds for species-specific and life stage-specific dose responses;
- Increasing understanding of the interaction of pelagic species (e.g., sharks, marine mammals, fish) with dynamic cables (i.e., cables in the water column); and
- Carrying out long-term, in situ studies to address the question of the effects of chronic EMF exposure on egg development, hatching success, and larval fitness.

3.3.1. ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Interest in EMFs has continued to grow in the four years since the publication of the *2020 State of the Science* report, and several studies have sought to improve understanding of the interactions between anthropogenic EMFs and marine species, with a strong focus on fish and invertebrates. Research has primarily involved controlled laboratory-based studies of anthropogenic B-fields (e.g., using Helmholtz coil devices), field-based surveys of EMF-emitting subsea cables, and a few numerical modeling studies.

It is important to note that several recent laboratory studies use much higher-intensity EMF levels than those expected from the subsea cables associated with current small-scale MRE developments, so their conclusions should be approached with caution. Very little research has been conducted on the effects at a scale relevant to MRE, and there is a need to assure realism about both the intensities and exposure timeframes used in experiments. Moreover, B-fields from anthropogenic sources are three-dimensional, but the experimental setups used in many laboratory studies only allow for the study of effects in two dimensions, so this and other study limitations should be considered.

Within the academic literature, several key reviews have also been published about the effects of EMFs on resource species (Hutchison et al. 2020) and early developmental stages of fish (Formicki et al. 2021), as well as the potential biological consequences of MRE deployments on marine species in general (Hemery et al. 2021a), modeling approaches for understanding environmental effects of MRE (Buenau et al. 2022), scaling up understanding of effects from single MRE devices to arrays (Hasselman et al. 2023), and marine animal displacement from EMFs generated from MRE devices (Hemery et al. 2024).

An expert workshop was held to advance understanding of EMFs from subsea power cables, with a particular focus on offshore wind, which developed several key outputs and recommendations (Gill et al. 2023). For example, the experts recommended that modeling of anthropogenic EMFs should also consider the local

geomagnetic field and prevailing water movement to determine the total EMF environment that an animal may encounter, and set out an agreed and standardized approach to determining the total EMF environment. The workshop also highlighted the importance of understanding the likelihood of animals encountering the total EMF environment when assessing potential impacts. Since this will depend on the presence and distribution of animals (spatially and temporally) and their use of the water column in relation to where the power cable (EMF source) is located, the experts suggested that a risk-based approach be explored (Gill et al. 2023).

Hermans et al. (2024) used an ecological risk assessment approach to determine the risk for behavioral effects of EMFs from offshore wind power cables on benthic elasmobranchs on the Dutch continental shelf. The study estimated exposure levels by comparing modeled B-fields to reported elasmobranch sensory ranges and effect levels, and found that potential risk levels differ depending on the biology and ecology of different species groups (e.g., rays, sharks, skates).

LABORATORY STUDIES ON FISH

Focusing first on the larval stage, Cresci et al. (2022a) exposed lesser sandeel (*Ammodytes marinus*) larvae to an artificial DC B-field gradient (50–150 µT) in a raceway tank to examine potential effects on their dispersal. Neither swimming speed nor distribution were affected, suggesting that lesser sandeel larvae will not be attracted to or repelled from subsea cables associated with MRE.

In a similar study, Cresci et al. (2022b) found that short-term exposure to an artificial DC B-field gradient (50–150 µT) also did not affect the spatial distribution of Atlantic haddock (*Melanogrammus aeglefinus*) larvae. However, the haddock larvae's median swimming speed and acceleration were significantly reduced, highlighting that B-field effects are species-dependent and individual-specific.

Building on these results, Cresci et al. (2023) exposed additional Atlantic haddock and Atlantic cod (*Gadus morhua*) larvae to artificial DC B-fields (22–156 µT) to assess effects on their dispersal. Short-term exposure did not affect the spatial distribution of either Atlantic haddock or cod larvae, but it reduced their swimming activity, suggesting that both species are sensitive to weak intensity B-fields.

Using a similar experimental setup but slightly higher intensities, Durif et al. (2023) tested whether short-term exposure to an artificial DC B-field (230 µT) affected juvenile lumpfish (*Cyclopterus lumpus*) behavior. While swimming speed was reduced (by 16%), swimming activity and distance traveled were unaffected, suggesting that lumpfish migration and homing would not be significantly affected.

In the first study to expose an elasmobranch to uniform AC and DC B-fields (450 µT), Albert et al. (2022a) observed the short-term behavioral responses of juvenile thornback rays (*Raja clavata*) in controlled conditions. Rays exposed to B-fields during the midday experimental period exhibited an increase in active behaviors, but those exposed during the morning period did not. Results highlight the challenges of studying species that display long periods of inactivity and high inter-individual variability, particularly with small sample sizes, and the need for further long-term studies.

Finally, Jakubowska et al. (2021) found that rainbow trout (*Oncorhynchus mykiss*) larvae reared in either AC (1 mT) or DC B-fields (10 mT) did not show direct avoidance after being re-exposed to their respective B-fields. Rather, the results highlight that early-life stages of rainbow trout can detect and are attracted to artificial B-fields, with no visible signs of stress (i.e., increased oxygen consumption).

LABORATORY STUDIES ON INVERTEBRATES

Beginning with behavioral effects, Albert et al. (2023) explored the potential behavioral effects on the commercially important velvet crab (*Necora puber*) from short-term exposure (30-min) to artificial AC and DC B-field gradients (72–304 µT). Results from three experimental setups suggested that these B-fields intensities do not induce attraction or repulsion, or affect the velvet crab's exploratory, foraging, and shelter-seeking behaviors.

In one of the first EMF studies on the filtration activity of suspension-feeding bivalves, Albert et al. (2022b) demonstrated that short-term exposure (6 h) to artificial DC B-fields (300 µT) had no observable effects on the filtering activity and filtration rate of the blue mussel (*Mytilus edulis*), a widespread ecosystem engineer and keystone species.

Chapman et al. (2023) found no significant differences in physiological stress responses in the common periwinkle (*Littorina littorea*), common starfish (*Asterias rubens*), European edible sea urchin (*Echinus esculentus*), and velvet crab after a 24-hour exposure to an artificial DC B-field (500 µT). The study also investigated exposure to the coastal invertebrates' righting reflex, which is an important measure of anti-predation, and found no significant behavioral effects.

Scott et al. (2021) investigated the behavioral and physiological effects of exposure to varying B-field strengths on the commercially important edible crab (*Cancer pagurus*). While exposure to 250 µT had limited influence, exposure to higher intensities (500 and 1000 µT) increased stress-related parameters; crabs exhibited an attraction to EMF exposed shelters and spent significantly less time roaming, once again highlighting the importance of understanding strength-dependent effects.

Moving to even higher intensities, Harsanyi et al. (2022) exposed ovigerous female European lobster (*Homarus gammarus*) and edible crab to DC B-fields (2.8 mT) throughout embryonic development. Although exposure did not alter embryonic development time, larval release time, or vertical swimming speed for either species, chronic exposure led to significantly smaller larval size in both species, a higher occurrence of larval deformities, and lower swimming test success rates amongst lobster larvae.

Jakubowska-Lehrmann et al. (2022) assessed the effects of high-intensity AC and DC B-fields (6.4 mT) on the bioenergetics and physiological processes of a common bivalve, the cockle (*Cerastoderma glaucum*). The filter feeder maintained a positive energy balance after exposure to both experimental conditions, but significant changes in filtration rate and other physiological effects were observed, revealing the potential for oxidative damage and neurotoxicity in invertebrates exposed to high-intensity B-fields.

Finally, using a combination of biochemical, metabolism, and transcriptome studies, Fei et al. (2023) found that prolonged exposure to an extremely high-intensity DC B-field (1.1 T) increased oxidative stress, blood glucose, and lipid levels, and decreased immunity and physiological conditions in a benthic sea slug (*Elysia leucolegnote*). However, these B-field intensities are, once again, much higher than those expected from any existing or planned MRE developments.

FIELD MEASUREMENTS AND MODELING

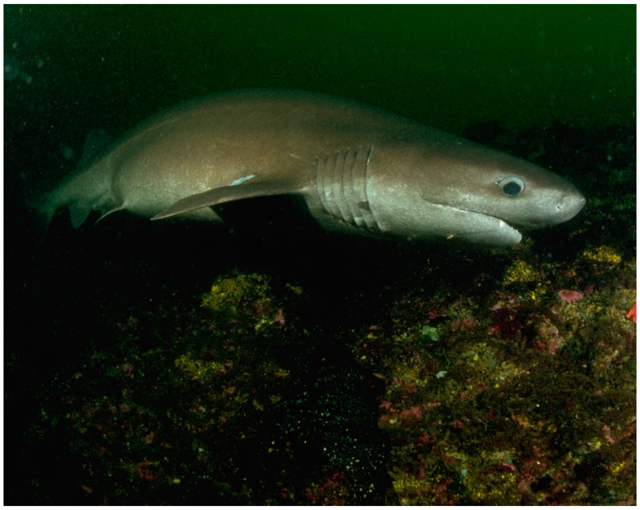
Since 2020, few studies have focused on quantifying the extent of natural and anthropogenic EMFs using field measurements and modeling, let alone the potential effects of EMF from MRE. Numerical modeling has been used to complement field and laboratory measurements, but the data needed for model validation are still lacking. EMFs can typically be modeled using analytical equations or numerical simulations, but applications have been constrained to simplified settings so far. A recent review of modeling approaches for understanding the environmental effects of MRE found no examples of realistic spatial variability or interacting fields, and no models of marine species' physiological or behavioral responses to EMFs (Buenau et al. 2022).

Building on the findings of Love et al. (2017), Williams et al. (2023) used experimental cages to study the response of red rock crabs (*Cancer productus*) to a 34.5 kV AC subsea transmission cable associated with an offshore oil and gas rig in the Santa Barabara Channel. Divers measured local B-fields near the cable, which peaked at ~1.2 µT along an exposed section and decayed to ambient levels 0.9 m away from the cable. The study found that red rock crab movement was not influenced by B-fields of similar intensity to those associated with existing MRE developments and was one of the first to measure the temporal variability of B-fields produced by a subsea transmission cable in situ.

Similarly advancing on previous work (Hutchison et al. 2018), Hutchison et al. (2021a) used the SEMLA sensor system to characterize the EMF emissions from an existing high voltage DC transmission cable and also conducted a tagging study to determine the potential encounter and responses of migratory American eels (*Anguilla rostrata*). Using high-resolution 2D and 3D telemetry data and modeling, the study found that while the eels moved faster when exposed to the DC B-field (-18 to 87 nT), the cable did not present a barrier to movement or migration.

In 2016, France Énergies Marines launched the SPECIES (Submarine PowEr Cables Interactions with Environment & associated Surveys) project to improve knowledge of the potential interactions between subsea cables and benthic organisms (Taormina et al. 2021). As part of the effort, the team conducted dynamic and static measurements of EMFs emitted by various subsea power cables using the PASSEM and STATEM tools (©MAPPEM). The PASSEM tool is towed by a surface vessel and can measure EMFs quickly over a wide area, but only at a single point in time and the movement creates noise in the data. Conversely, the STATEM tool is a stationary device that can measure EMFs over time and assess variations near signal sources.

Grear et al. (2022) tested two commercial-off-the-shelf instruments for measuring background B-fields at MRE sites, as well as a third sensor for improving the certainty of location measurements. Results from field testing at Pacific Northwest National Laboratory's Marine and Coastal Research Laboratory in Sequim, Washington suggested that background variability and anomalies in the B-field (on the orders of 10-100 nT) may make it difficult to measure distortions in the



local field from relatively low power cables. Lessons learned and recommendations for measuring background B-fields at potential MRE sites are highlighted.

Based on the open-source Arduino platform, Luna et al. (2023) developed a low-cost device capable of detecting B-fields generated by a subsea cable. Results from laboratory and field tests confirmed that the device could take and store measurements at depths of up to 150 m, with about 10 µT accuracy.

As part of the Wave Energy in Southern Europe (WESE) project, Chainho & Bald (2020) conducted EMF surveys around the cable serving IDOM's MARMOK-A-5 wave energy device at the Biscay Marine Energy Platform (BiMEP) test site in Spain. However, no EMF signals could be identified as originating from the cable, likely due to the low power output of the device at the time.

Chainho & Bald (2021) also developed an open-source EMF modeling tool based on Python code and Finite Element Method Magnetics software to estimate EMF strength around the cables serving the MARMOK-A-5 device at BiMEP and the Waveroller device at the Peniche test site in Portugal. In both cases, the EMFs were small, decayed exponentially with distance, and reduced by at least one order of magnitude at 1 m from the cable. Lacking quality data from the deployments to validate their modeling, the team compared their results to a previous study (Slater et al. 2010) and found good correlation.

Hutchison et al. (2021b) used computational and interpretive models to explore the influence of cable properties and burial depth on the DC magnetic field produced by a bundled high voltage DC transmission cable. The study demonstrated the need to consider cable properties and burial when determining the strength and

extent of B-fields emitted and encountered by receptive species. Cables are unlikely to be buried at the same depth along the length of the cable, so the EMF will vary along the cable route.

3.3.2. STATUS OF RISK RETIREMENT

Based on existing evidence, there is consensus among the scientific community that EMFs from small-scale MRE developments (one to six devices) are not harmful and do not pose a risk to marine animals, and therefore should not inhibit the installation of devices or require extensive monitoring (Copping et al. 2020a, Copping et al. 2020b, Gill & Desender 2020). The risk of EMFs for new MRE projects with small numbers of devices can be retired. Recent investigations have improved understanding of the interactions between EMFs and some fish and invertebrate species, but their conclusions should be approached with caution given the unrealistically high intensities used in some study designs.

OES-Environmental has developed an EMF Evidence Base listing the key research papers and monitoring reports that define what we understand about EMF effects, and an EMF Guidance Document to evaluate EMF effects within a general regulatory context.

3.3.3. RECOMMENDATIONS

While some progress has been made to address the research and monitoring needs identified in the *2020 State of the Science* report (Gill & Desender 2020), several gaps remain. Additional research and monitoring are needed to:

- validate existing models with field measurements from deployed MRE device cables;
- increase understanding of responses to EMFs at more realistic intensities and temporal patterns of power transmission by MRE devices;
- determine the total EMF environment, which will involve modeling and measurement of cable (or other source) EMFs, local geomagnetic fields, and prevailing water movement interactions;
- determine thresholds for species-specific and life stage-specific dose responses; and
- increase the understanding of the interaction of pelagic species (e.g., sharks, marine mammals, fish) with dynamic cables.

Additionally, EMF models for MRE are still in early stages and require further development for complex layouts, field validation, and incorporation of species-response data from controlled laboratory studies to assess potential long-term effects (Buenau et al. 2020). MRE developers and the cable industry should make cable properties and energy transmission data available to improve modeling and enable realistic environmental assessments. The development of environmental standards or guidelines for subsea cable deployment and the measurement of EMFs would also assure that data are transferable and can inform future developments. Finally, as larger MRE projects are planned alongside additional offshore energy development, the cumulative EMFs from multiple subsea cables and substations must be measured and these levels evaluated relative to what is known about marine animal sensitivities.

3.4.
CHANGES IN BENTHIC AND PELAGIC HABITATS CAUSED BY MARINE RENEWABLE ENERGY DEVICES

Author: Lenaïg G. Hemery

Benthic (seafloor) and pelagic (water column) habitats provide the biological and physical resources that marine animals rely on to live, including food and shelter. Like any artificial structure added to the marine environment, MRE devices and associated infrastructure may alter benthic and/or pelagic habitats and affect marine organisms (Figure 3.4.1). Bottom-mounted MRE devices are often attached to the seafloor by gravity foundations or pin piles, while floating devices are secured in place with anchors and mooring lines. Power is typically exported to shore by cables buried in the sediment, running along the seafloor, or draped in the water column between devices in a floating array. Usually, the environmental impact assessment stage identifies fragile, unique, or important habitats, which helps in siting projects away from those areas, and mitigating (i.e., avoid, reduce, or compensate for) any severe habitat changes. Nonetheless, the installation, presence, operation, and removal of MRE devices inevitably lead to some changes in marine habitats that may differ from natural variability. The nature of such changes may be neutral, negative, or possibly positive, for the environment.

The range of potential changes in benthic and pelagic habitats related to the various phases of MRE development (Hemery 2020; Hemery et al. 2021b; Martínez et al. 2021) is listed below and shown in Table 3.4.1:

- Loss of some habitat during installation immediately under device foundations, anchors, and cable protections; of colonized infrastructure upon removal; and of benthic and pelagic habitats and habitat connectivity due to the presence of operating devices and associated structures;
- Disturbance and potential removal of sediment during installation and removal of cables and devices, as well as scour of fine sediment around bottom structures;
- Increased turbulence and changes in flow velocity around the base of devices, affecting less resilient benthic organisms;

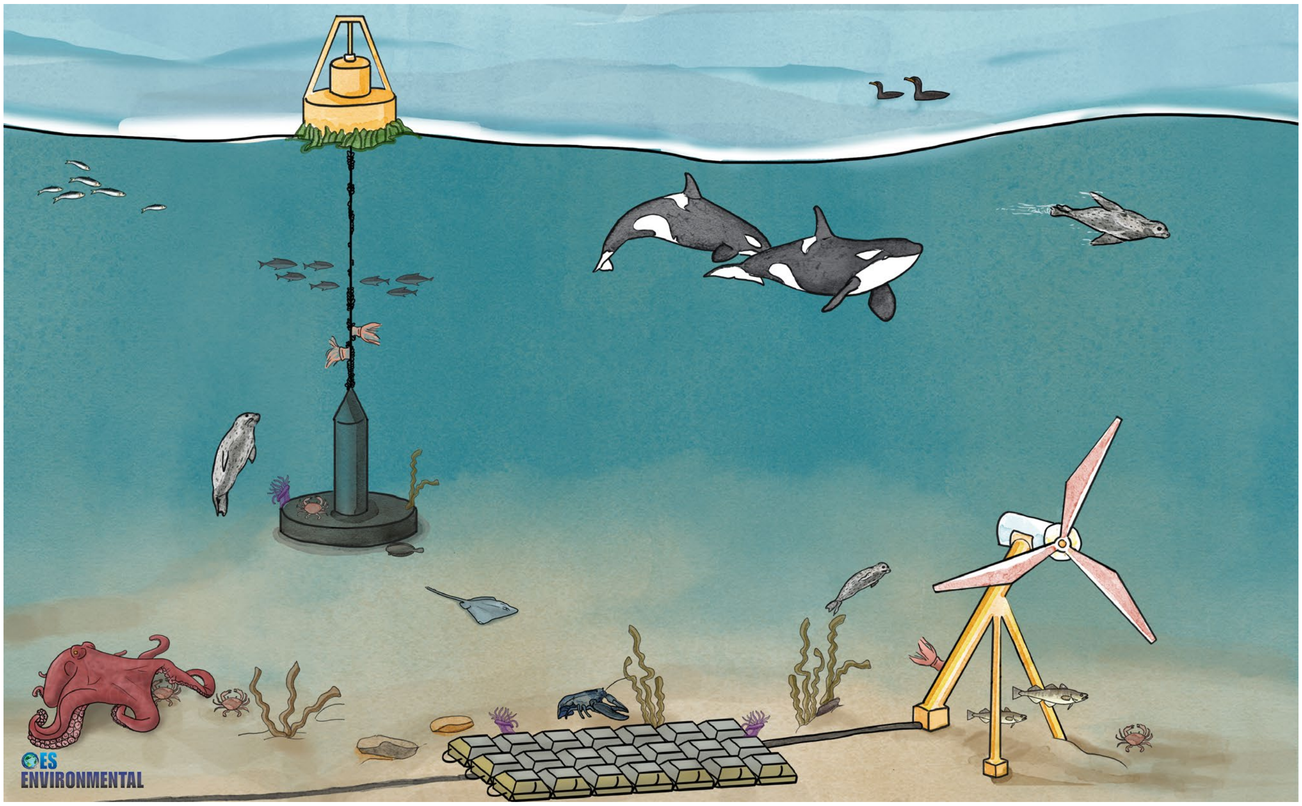


Figure 3.4.1. Representation of a temperate ecosystem with benthic and pelagic habitats influenced by a wave energy converter, a tidal turbine, and an export cable protected by a concrete mattress. (Modified from Hemery et al. 2021a)

- Colonization of new hard structures by biofouling organisms, possibly non-native invasive species, impacting local biodiversity;
- Attraction of mobile organisms to the devices and associated infrastructure acting as artificial reefs and shelters, increasing local biodiversity and prey availability;
- Local increase of biomass inside a project area, potentially acting as a marine reserve; and
- Enrichment of the surrounding seafloor with organic matter and nutrients due to increased biomass on and around the devices, with cascading effects on biogeochemical processes and benthic diversity.

Any animal species within a marine ecosystem may be affected by changes in benthic and pelagic habitats related to MRE development. For instance, individual sessile organisms may be lost during the installation phase, because they are unable to relocate, but the population may gain new habitat by colonizing the devices; mobile benthic and demersal animals may find new habitats on and around the foundations, anchors, and cable protections; non-native species, potentially invasive, may establish themselves on the new substrates; small pelagic fish may benefit from the food and protection provided by devices and mooring systems in the water column; and marine predators may take advantage of greater prey availability in the vicinity of MRE devices (Copping et al. 2021b; Hemery et al. 2021b; Martinez et al. 2021).

Table 3.4.1. Potential changes in benthic and pelagic habitats related to marine renewable energy (MRE) devices. Unless specified, the references provided in the descriptions of the potential changes are from an MRE context. References from surrogate industries were used when necessary.

Potential Changes	Description	Development Phase	Benthic or Pelagic
Loss of habitat	Inaccessibility of seafloor habitat directly underneath device foundations, anchors, and cable protections; proper siting will identify fragile habitats and avoid critical habitat loss (Hemery 2020) Presence of operating devices and associated structures may prevent access to certain habitats and limit connectivity (Miller et al. 2013) Habitat of colonized structures will be lost upon device removal (Miller et al. 2013)	Installation, operation, decommissioning	Benthic, pelagic
Sediment disturbance	Disturbance of soft/unconsolidated sediment habitats because of • Trenching or digging to install cables (Taormina et al. 2018), • Resuspension of fine sediments upon installation and removal of bottom structures (Taormina et al. 2018), • Scouring of sediment around structures due to localized turbulence (e.g., Davis et al. 1982, in the general context of man-made structures), and/or • Sweeping of seafloor areas by catenary mooring chains around anchors (e.g., Morrisey et al. 2018, in the context of boat moorings)	Installation, operation, decommissioning	Benthic
Footprint effect	Increased turbulence and changes in flow velocity around bottom structures can affect epibenthic organisms (O'Carroll et al. 2017a)	Operation	Benthic
Biofouling	Colonization of devices and associated components by sessile organisms or life-history stages, potentially non-native species (Macleod et al. 2016)	Operation	Benthic, pelagic
Artificial reef effect	Attraction of mobile animals to the devices and associated components for food and/or shelter (Langhamer, 2012)	Operation	Benthic, pelagic
Reserve effect	Local populations boost because of cessation or modification of fishing and other human activities in the project area (Alexander et al. 2016)	Operation	Benthic, pelagic
Seafloor enrichment	Accumulation of organic matter and decaying shells on/in the seafloor around devices due to increased litter falls from biofouling organisms and animals attracted to the artificial reef (Wilding 2014)	Operation	Benthic

As of 2020, most MRE studies investigating changes in benthic and pelagic habitats focused on the effects associated with the installation and presence of cables (e.g., Sheehan et al. 2020; Taormina et al. 2018); the footprint effect around tidal turbine foundations (e.g., O'Carroll et al. 2017a, 2017b); biofouling and the colonization by non-native species (e.g., Loxton et al. 2017; Macleod et al. 2016; Taormina, 2019; Want et al. 2017); the artificial reef effect of both MRE devices and their cables (e.g., Bicknell et al. 2019; Langhamer 2016; Sheehan et al. 2020; Taormina et al. 2018); and the reserve effect through modeling (Alexander et al. 2016).

Priority recommendations listed in the *2020 State of the Science* report (Hemery 2020) included:

- improving the understanding of marine animals' spatial and temporal distribution and habitat use in areas targeted for MRE development;
- conducting studies to clarify biofouling and artificial reef assemblage compositions and succession stages; and
- increasing the use of numerical models to assess habitat changes.

3.4.1. ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Since the publication of the *2020 State of the Science* report, many new MRE-specific studies have been released in alignment with the recommendations noted above, as well as increased focus on the development of monitoring technologies.

UNDERSTANDING ANIMALS' DISTRIBUTION AND HABITAT USE IN MRE AREAS

Most studies related to changes in habitats published since 2020 have been observational in nature and focused on animal distribution and use of tidal habitats. Receptors included marine mammals (mainly seals and harbor porpoises), fish, diving seabirds, and seafloor assemblages (i.e., benthos). These studies can be used as baseline information for future investigations of potential effects.

Marine mammals

To better characterize the risk of harbor seals colliding with tidal turbines, Onoufriou et al. (2021) equipped the animals with telemetry tags to quantify changes in distribution between pre- and post-installation and operation of the MeyGen tidal turbine array (Scotland, UK). Seals were shown to use the area closer to shore during the ebb tide and to be more dispersed offshore during the flood tide. There were no significant differences in seal distribution between pre- and post-installation survey periods. However, most seals remained about 2 km away from the array area when the turbines were operational.

Palmer et al. (2021) used acoustic surveys to assess the presence of harbor porpoises in close proximity to one of the operating MeyGen tidal turbines in the context of collision risk. In addition, they used the data to characterize their temporal habitat use of the tidal channel. They recorded intra-annual and diurnal variations in animal presence, across tidal states. Harbor porpoises were more abundant during winter, at night, and during the peak of flood tide, and less abundant when the tidal turbine was operating.

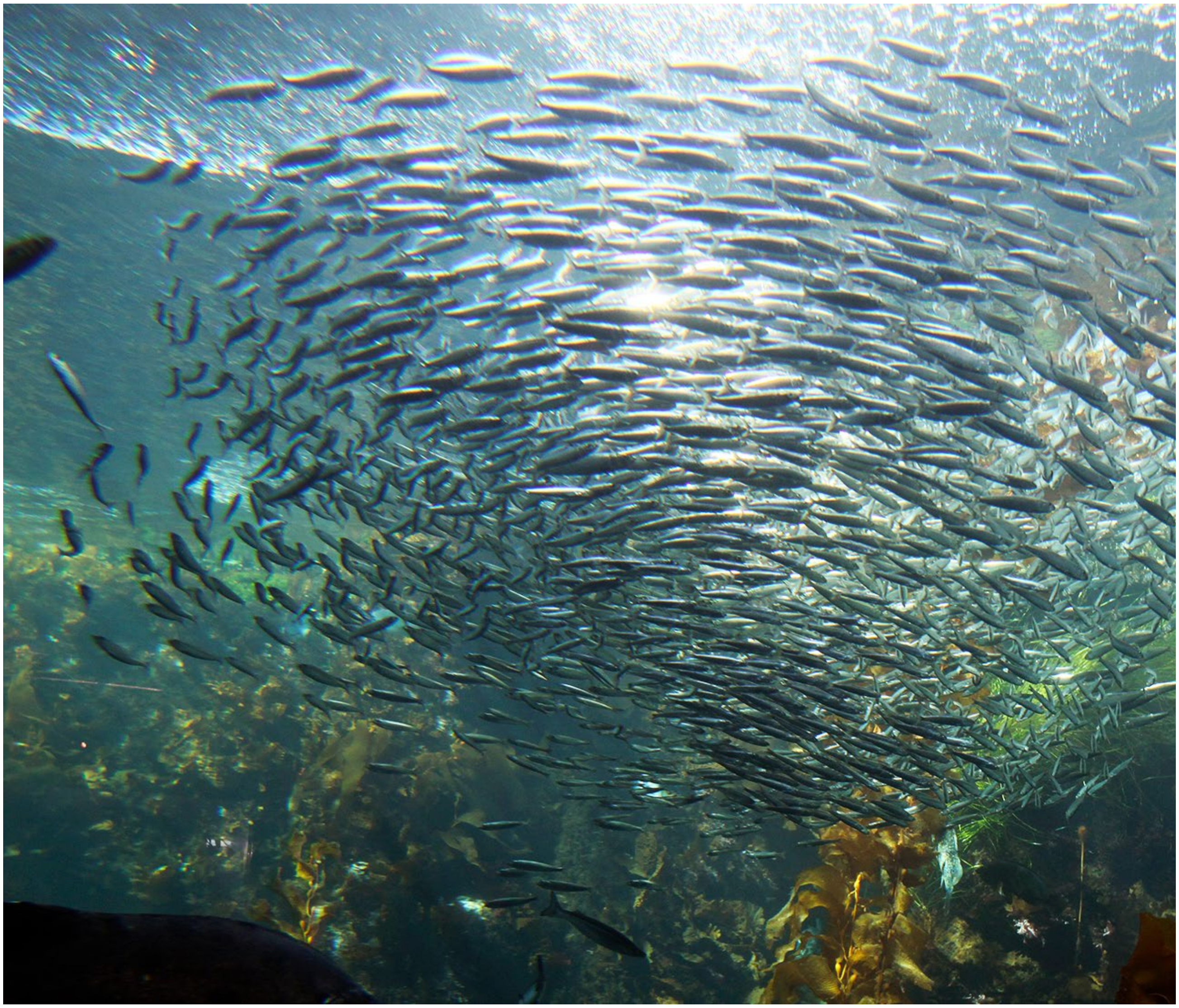
Land-based visual surveys by human observers and turbine-mounted video cameras were used over several years to assess the presence of animals around the Nova Innovation's Shetland tidal array on Bluemull Sound (Scotland) (Smith, 2021; Smith et al., 2021). In nine years of surveys (2010-2019), marine mammals were recorded infrequently in this tidal channel, with harbor seals recorded in 12% of surveys and harbor porpoises in 6% of surveys. In addition, harbor seals were seen on the video footage around the turbines on nine individual days, but no occurrences of harbor porpoise were ever recorded on video.

Marine fish

As part of a baseline characterization survey of a potential tidal energy site in the Banks Strait (Australia), Scherelis et al. (2020a) estimated small-scale cyclical changes in fish density distributions using sonars during a two-week campaign. Results showed that fish densities were significantly highest at night, at high current speed (1.75 to 2.0 m/s), in the 20 to 40 m depth range, close to the seafloor, especially in areas 15 to 40 m deep. Water temperature and seafloor habitat type did not explain fish density distributions. In a related baseline characterization study, Scherelis et al. (2020b) measured fish aggregation metrics over 2.5 months using an integrated multi-instrument platform. Fish were significantly more abundant, less aggregated, and closer to the seafloor at night and at higher water temperatures. Fish abundance was also positively correlated with current speed, especially during ebb tides.

The turbine-mounted video camera at the Nova Innovation site recorded footage of groups of saithe/pollock throughout the year, swimming around the turbine at slack tide or low current speeds, sometimes feeding on the biofouling growing on the nacelle (Smith 2021). Most fish were observed swimming toward the seafloor once currents reached the turbine cut-in speed of 0.8 m/s.

Whitton et al. (2020) assessed fish school vertical distribution at a site targeted for deployment of a Minesto tidal kite off the west coast of Holy Island, UK, using sonars and trawl samples. Schools of sprat (*Sprattus sprattus*) and whiting (*Merlangius merlangus*) were present throughout the 3.5-month long survey and undertook diel vertical migrations to disperse at the surface in the evening and regroup at depth (on average 20 m deep) in the morning. However, fish schools were deeper in October (≈ 22 m) than in January (≈ 15 m).



Seabirds

To evaluate potential impacts of tidal turbines on seabird foraging habitats, Couto et al. (2022) conducted transect surveys to correlate seabird foraging distribution with physical hydrodynamics and prey presence. The distribution of benthic foraging seabirds was strongly associated with sandeel habitats and water velocities below 1.5 m/s. On the other hand, pelagic foraging seabirds were observed in the entire study area and their distribution was strongly associated with fast water velocities (1.5 to 3 m/s) and the presence of fish schools.

Isaksson et al. (2021) used telemetry biologgers to track habitat use by European shags (*Phalacrocorax aristotelis*) in the Pentland Firth tidal stream (Scotland). While the shags clearly used the tidal stream for foraging, few were observed at the location of the turbines within the MeyGen lease area. Johnston et al. (2021) also equipped black guillemots (*Ceppus grylle*) with GPS trackers to evaluate their use of Pentland Firth as foraging habitat. Black guillemot foraging preferences were predominantly associated with water depths of 32 m and current speeds of 1.5 m/s in the MeyGen tidal lease area, and with water depths of 25 m and current speeds of 0.8 m/s outside of the lease area.

Using small uncrewed aerial systems (UAS), or drones, Lieber et al. (2021) focused on three species of surface-foraging terns and their use of physical hydrodynamics as foraging cues in Strangford Lough (Northern Ireland, UK) around the non-operational SeaGen turbine. Terns were more likely to actively forage in turbulent areas with strong vorticity and swirling flows. Small UAS were also used to survey pursuit-diving seabirds of the auk family in the Pentland Firth and their association with bed-derived turbulent features observed at the sea surface, called kolk-boils (Slingsby et al. 2022). The auk density distribution was correlated with the periphery of kolk-boils and influenced by the current velocity and tidal phase.

Based on visual surveys by human observers and turbine-mounted video footage at the Nova Innovation site, black guillemots and European shags were infrequently observed diving in the array area, although more often at slack ebb tides and flood tides than during ebb tides (Smith 2021; Smith et al. 2021). Both seabird species were observed on the underwater video footage on a few occasions when the turbines were not operating. A European shag was seen chasing a school of fish by the idling turbine.

Benthos and seafloor habitats

An environmental survey was conducted two years after the deployment of a wave device at King Island, Australia, characterizing the seafloor habitats with underwater videos (Marine Solutions 2023). The sediment around the device was free of megafauna and macroalgae; however, the device itself was covered in green algae, snails, barnacles, and sponges. The two control sites differed from the device site; they had higher abundances of brown and turf algae, as well as fish and sea urchins.

Smyth and Kregting (2023) conducted scuba surveys to characterize the seafloor assemblages prior to the deployment of the Minesto kite in Strangford Lough, and after five years of operation. No significant differences were found in substrate type, species diversity, or species abundance over the five-year period, leading the authors to conclude that no changes in benthic habitats were detectable as a result of the kite installation and operation.

UNDERSTANDING BIOFOULING AND ARTIFICIAL REEF ASSEMBLAGE COMPOSITIONS

An additional number of studies published since the release of the *2020 State of the Science* report have focused on the marine species and assemblages growing on devices (i.e., biofouling) or the animal communities that aggregate around the devices, their mooring systems, and the cables (i.e., the artificial reef effect).

The studies assessed whether the faunal communities on or around the devices differ from those in surrounding natural habitats and may increase local biodiversity and/or modify local food webs. In addition, understanding biofouling diversity, abundance, and succession stages can also help inform device developers about antifouling strategies.

Biofouling

In Orkney Islands (Scotland), Nall et al. (2022) reported the growth of biofouling organisms, focusing on non-native species, on settlement plates of different colors and coatings. Differences in assemblage composition but not biofouling cover were observed between plate colors, although diminishing over time, while composition and cover differed between coating types. Few non-native species were observed on the settlement plates. Want et al. (2021) deployed settlement plates of various material and coatings at 25–40 m deep in high-energy and sheltered sites in the Orkneys. After a few months, a succession from hydroid-dominated to tube-forming amphipod-dominated communities was observed at all sites, while solitary tunicates dominated only at the sheltered site. Want et al. (2023) identified three biofouling assemblages based on site hydrodynamics and water depth: deep and shallow tidal, deep and shallow wave, and harbor and marina. No non-native species were detected. They also reported the first near-surface observation of large size acorn barnacles (*Chirona hameri*) on uncoated parts of a floating tidal turbine, potentially posing challenges if left unchecked.

Portas et al. (2023) used a multidisciplinary approach to understand how hydrodynamics affect biofouling communities on artificial structures in a tidal estuary in Brittany (France). Biofilm species and assemblages of macro-organisms greatly differed between sampling sites of high and low velocity, with higher proportions and diversity of macro-organisms under low shear stress conditions.

Vinagre et al. (2020) compiled a database of qualitative and quantitative information about sessile biofouling species present in European waters, including non-native species, associated with MRE devices and related infrastructure as well as other artificial substrates. The database provides information related to biofouling species composition, thickness, weight, and size.

Artificial reefs

In Sweden, at the Lysekil research site, 21 gravity-based foundations without WECs attached were installed in the mid-2000s (Bender et al. 2020). Surveys to characterize their colonization by mobile invertebrates and demersal fish were performed shortly after installation and 12 years later, and showed a clear artificial reef effect with greater species richness, diversity, and abundance at the foundations than at the control sites. At wave energy sites along the Swedish coast, Bender (2022) found that the no-take zone positively affected decapod and sea pen abundance and size, despite strong interannual variation. At the Sotenäs project site, an underwater video survey was conducted where the foundations of 34 WECs remain on the seafloor after the project was canceled (Bosell et al. 2020). Five years after installation and bottom-trawling ban, structures were heavily colonized by sessile and mobile invertebrates and fish, some of them listed as near threatened or vulnerable species. This led the structures to remain at the site as an artificial reef and no-take zone for trawling.

At the Paimpol-Bréhat tidal test site in France, Taormina et al. (2020a) monitored concrete mattresses protecting a cable during five years. These structures provided habitat for benthic megafauna, including edible crabs, European lobsters, European congers (*Conger conger*), and Ballan wrasses (*Labrus bergylta*). The degree of colonization of the structures was correlated with the number and type of available shelters. Leveraging four years of underwater imagery surveys of artificial structures, Taormina et al. (2020b) characterized the artificial reef effect and the ecological succession stages. The epibenthic communities on the artificial structures were significantly more diverse than in the surrounding natural habitats, but were not yet stabilized at a mature succession stage. They noted that community changes can still occur five years post-installation.

INCREASING THE USE OF NUMERICAL MODELS

When sufficient input of good quality data are available, numerical models allow researchers to investigate the distribution of marine species in areas suitable for MRE projects, and to assess the habitat use and connectivity within and between project sites. Ecosystem models can also be computed to investigate effects through food web networks (see Chapter 9). However, models are an estimation and will ultimately need to be tested against real data.

Baker et al. (2020) used an approach combining species distribution and hydrodynamic models to examine the impact of a potential tidal barrage on 14 species linked by predator-prey relationships. In the exercise, species of lower trophic levels were negatively affected by losing distribution areas, while higher trophic levels gained habitat behind the tidal barrage, altering the food web dynamics.

Using acoustic telemetry and physical oceanography data with a species distribution model, Bangley et al. (2022) developed a predictive distribution of striped bass (*Morone saxatilis*) in the Minas Passage of the Bay of Fundy (Nova Scotia, Canada). The model indicated that the fish were more likely to be present within the area of the FORCE tidal test site at relatively higher water temperature during late ebb tides.

Buenau et al. (2022) reviewed the modeling approaches employed for multiple stressor-receptor interactions specific to MRE, including changes in habitat. While a large diversity of applicable models exists, this study found that few had been applied in the MRE context at the time of writing. Although advocating for greater use of these models, the authors cautioned about their limitations and that good quality input data are essential, especially when pairing habitat and hydrodynamic models.

HABITAT MONITORING TECHNOLOGIES AND APPROACHES

While technologies employed to monitor benthic and pelagic habitats around MRE devices do not differ from those commonly used by other fields of marine ecology, newer technologies were recently applied in the MRE context. In addition, recent studies have looked at applying more automated ways of detecting and identifying animals around MRE devices and associated structures. More details about monitoring technologies and plans are provided in Chapter 2.

Hemery et al. (2022a) identified 120 monitoring technologies that can be or have been applied in the MRE context to survey six main habitat categories: seafloor, sediment, infauna, epifauna, pelagic, and biofouling. These technologies belong to 12 broad methodology classes: acoustic, corer, dredge, grab, hook and line, net and trawl, plate, remote sensing, scrape sampling, trap, visual, and others (e.g., environmental DNA). Visual technologies were the most common and diverse and were applied across all six habitat categories.

Hemery et al. (2022b) used a 360-degree underwater video lander for the first time around a WEC to assess its usability for monitoring the artificial reef effect of the device's mooring system. The 360-degree field of view enabled the successful recording of fish activity around the anchor during most of the camera deployments.

Costagliola-Ray et al. (2022) assessed the efficacy of UAS for collecting at-sea abundance and distribution data of surface-foraging seabirds like terns in a tidal stream environment as compared to land-based vantage point surveys. The two types of surveys provided similar results, though UAS enabled the identification of fine-scale distribution patterns. However, vantage point surveys are less dependent on weather conditions and visibility. Approach choice should thus be case specific.

To generate benthic habitat maps at MRE sites, Revelas et al. (2020) tested a new sediment profile imagery system at the PacWave test site off Newport, Oregon, alongside acoustic seafloor surveys. The results enabled the generation of Coastal and Marine Ecological Classification Standard benthic habitat maps using a repeatable and cost-effective approach.

Taormina et al. (2020c) optimized an automated process called "point count" to detect, identify, and quantify benthic organisms on still images. They successfully applied their process to images of benthic communities established on cable protection mattresses at the Paimpol-Bréhat tidal test site, where the three-dimensional structure was low and macroalgal coverage minimal.

3.4.2.
STATUS OF RISK RETIREMENT

To move forward on risk retirement for changes in habitat, OES-Environmental has developed a Habitat Change Evidence Base listing the key research papers and monitoring reports that define what the research community understands about this stressor-receptor interaction. Additionally, a Habitat Change Guidance Document was developed to evaluate changes in benthic and pelagic habitats within a general regulatory context.

The evidence base to date, along with discussions with subject matter experts, suggests that the changes in benthic and pelagic habitats caused by single devices or small numbers of MRE devices are well understood (Hemery et al. 2021b). Monitoring studies around devices and associated structures at completed and ongoing MRE projects have shown that the short-term effects (i.e., up to 3–5 years of monitoring) on species assemblages and distribution, or on sediment composition, are similar to those of other existing human activities at sea. While there will always be some differences among sites and the associated living resources, in general these studies have shown that changes in habitats from operational MRE devices are not likely to cause injury or harm to marine organisms, that severe effects can be mitigated by identifying and avoiding of fragile habitats, and that habitats recover quickly from the disturbance. In addition, habitat changes observed to date at single devices and small arrays are hardly discernable from the natural variability, especially after a dozen years (Bender et al. 2020). Subject matter experts have agreed that these studies have gathered enough scientific information to support retiring the risks related to short-term changes in habitat for new projects with small numbers of devices (one to six devices), recommending that regulators, advisors, and developers leverage the knowledge gained from previous projects and surrogate industries (Hemery et al. 2021b).

However, some remaining knowledge gaps prevent a full understanding of the effects of single devices and small arrays on benthic and pelagic habitats (Table 3.4.2). While a lot can be learned about the effects of WECs and device foundations or anchoring systems from studies conducted around fish aggregating devices, artificial reefs, or hydrographic buoys, the lack of true surrogates for tidal energy devices limits the information transfer from other marine industries. Additionally, most studies on habitat changes have been conducted so far in temperate ecosystems of the northern hemisphere. There is a lack of information regarding potential effects of MRE devices on mangrove, seagrass, coral reef, and coastal lagoon habitats more common in tropical and subtropical areas (Martinez et al. 2021; see Chapter 10).

Furthermore, guidelines are needed for spatiotemporal scales that would enable the identification of changes associated with long deployment timeframes and assess the success of monitoring and mitigation measures. Nonetheless, while no guidelines specific to MRE for monitoring marine habitats and collecting field datasets currently exist, the industry can leverage two International Organization for Standardization (ISO) guidelines (ISO 16665 on soft-bottom substrate, and ISO 19493 on hard-substrate seafloor), as well as a dozen US and UK guidelines for monitoring habitats in the context of renewable energy at large, or in the context of extractive industries such as oil and gas or dredging. More details about how these guidelines could apply in the MRE context are provided in Hemery et al. (2022c). Careful judgment is recommended when leveraging these guidelines because an abundance of sampling technologies, methods, sampling designs, and data analyses are provided, but may not always be applicable nor necessary around MRE devices.

As the MRE industry scales up to large arrays (10–30+) and moves toward the decommissioning of completed projects, significant knowledge gaps persist that prevent fully retiring the risks (Table 3.4.2). These knowledge gaps mainly relate to the fact that effects on habitats may not scale linearly with the area occupied by an array or with the number of devices, and that effects may vary across spatial and temporal scales (Hasselman et al. 2023). Numerical models can help evaluate and predict changes in habitats within and around arrays, but high-quality field datasets on both the receptors and the local and regional environmental conditions are necessary as inputs and for output validation (Buenau et al. 2022; Hasselman et al. 2023).

Table 3.4.2. Knowledge gaps by category of changes in habitats. International researchers focusing on changes in habitats caused by marine renewable energy (MRE) devices gathered at a workshop in 2021 to discuss the potential for retiring the risks associated with habitat change as well as identified the remaining uncertainties and knowledge gaps. This table summarizes, per category of habitat change, the main knowledge gaps that will help with consenting and licensing of small numbers of MRE devices once addressed (middle column), and that will help ease concerns related to deploying large arrays or decommissioning MRE (right column).

Categories	Single Devices & Small Arrays	Large Arrays or Decommissioning
Effects of installation and removal on benthos	• Post-installation monitoring is typically not completed on long-enough timeframes to fully understand effects	• Effects from decommissioning or removal are less understood due to the nascent status of the industry and will need to be carefully studied • Monitoring is still needed to support modeling and validation of the impacts of arrays
Community composition on or near devices	• Identification of the appropriate level of site-specific study and monitoring is necessary • Established guidelines, standard mitigation, and frameworks for monitoring and characterizing risks are needed • Ongoing concerns about biofouling by non-native or invasive species remain	• 1–6 devices are not expected to have effects on the seabed, but it depends on how long they are in the water and the colonizing species • Monitoring is still needed to support modeling and validation of the impacts of arrays • Lack of information about whether effects on functional diversity are similar to those observed on taxonomic diversity • The mechanisms of colonization by non-native species are not sufficiently well understood, though some data exist Examples in a variety of geographic regions are missing • Ongoing concerns about biofouling by non-native or invasive species remain
Artificial reef effect	• Remaining concerns about artificial reef effects may be better alleviated with post-installation monitoring • Uncertainties remain about whether the artificial reef is representative of the existing surrounding community or is an attraction to new species	• Uncertainties remain about whether the artificial reef is representative of the existing surrounding community or is an attraction for new species • The potential effects on fish stocks and aquaculture need to be evaluated over the long term • Apprehending local flow conditions is necessary for understanding the artificial reef effect
Habitat change overall	• Wave and tidal environments need to be considered separately • Risks to habitats in tidal environments will be more difficult to retire due to current knowledge gaps and difficulties involved in monitoring • There is a lack of guidelines on appropriate timescales for studying effects, especially in anticipation of decommissioning	• There is a lack of guidelines on appropriate timescales for studying effects, especially in anticipation of decommissioning
Learning from surrogate industries	• Unlike for wave energy environments, good surrogates for tidal environments are still missing • Data transferability from surrogate industries is important, but transferred data need to be evaluated by experts to assure their relevance for a specific project	

Source: Hemery, L.G., Rose, D.J., Freeman, M.C., Copping, A.E., 2021b. Retiring environmental risks of marine renewable energy devices: the “habitat change” case. Presented at the 14th European Wave and Tidal Energy Conference (EWTEC 2021)

3.4.3. RECOMMENDATIONS

While some progress has been made in the last four years toward realizing the recommendations listed in the *2020 State of the Science* report (Hemery 2020), all these recommendations remain valid to date. Additional recommendations are provided below.

- MRE project proponents should consult with various actors in the targeted areas early on to assess the availability, quality, and applicability of existing datasets before collecting any new baseline habitat data. Various government agencies, academic researchers, and other entities may collect habitat-related field data (e.g., species composition, abundance and diversity, sediment characteristics, water quality parameters) in areas targeted for MRE development long before a wave or tidal project is proposed. Local users, such as Indigenous groups and commercial fishers, may also have historical knowledge of local marine habitats to share. Consultation with existing marine spatial planning commissions is also advised. When the collection of new field data is necessary, the protocols used must be similar to allow for comparison with suitable datasets. In addition, leveraging multiple datasets might help address questions at multiple spatiotemporal scales.
- A careful review of biodiversity and habitat quality indices may identify one that is more suitable to the international MRE context, or highlight a pathway for creating such a universal biodiversity and habitat quality index. While the existing indices (e.g., the AZTI Marine Biotic Index (Borja & Muxika 2005), the Benthic Habitat Quality index (Nilsson & Rosenberg 1997), or the Coastal and Marine Ecological Classification Standard (Federal Geographic Data Committee & Marine and Coastal Spatial Data Subcommittee, 2012)) are useful metrics, they are often region- or country-specific and difficult to transfer from one project to another for risk retirement purposes.
- As much as possible, automated image post-processing and annotation methods (e.g., using machine learning or other artificial intelligence approaches) should be used to dedicate most resources to species identification and data analyses (Love et al. 2023; Signor et al. 2023; Taormina et al. 2020c). Underwater still and video imagery technologies are among the most common methods used for surveying benthic and pelagic habitats (Hemery et al. 2022a); however, the data processing is cumbersome and resource intensive.
- While protocol optimizations remain necessary, the environmental DNA (eDNA) approach enables the collection of information on animals' presence, diversity, and distribution from water samples only. Conventional monitoring technologies may not always be adapted to the high-energy marine environments targeted for MRE deployments, and cost-efficient alternatives such as eDNA are becoming reliable and more mainstream (Capurso et al. 2023; Fu et al. 2021; Williford et al. 2023).

3.5.
CHANGES IN OCEANOGRAPHIC SYSTEMS ASSOCIATED WITH MARINE RENEWABLE ENERGY DEVICES

Author: Jonathan M. Whiting

The movement of ocean water is caused by large-scale forces including the gravitational attraction of the earth with the sun and moon, the rotation of the earth, and the shape of continents, surface winds, and density-driven convection currents between the ocean depths and the surface. The resulting waves, tides, and persistent ocean currents distribute heat and water masses, and materials including sediments, dissolved gasses, and nutrients, which in turn help support marine and coastal ecosystems. MRE devices deployed at sea have the potential to change flow patterns, wave climates, and remove energy from the system (Whiting et al. 2023). If large enough, these resulting changes may interrupt natural flows, changing habitats for some marine organisms and potentially affecting marine food webs (Martínez et al. 2021b). As greater numbers of devices are deployed, the resource (tidal, wave, ocean currents) is likely to be increasingly affected, changing flows, wave heights, or density structures in the ocean. Changes in oceanographic systems associated with the presence of MRE devices have not yet been observed in the ocean as only small numbers of devices have been deployed to date, resulting in immeasurably small changes. Modeling studies have focused mainly on predicting changes in oceanographic systems from large numbers of devices, often greater than 30 devices, informing our understanding of how changes compare with natural variability (e.g., De Dominicis et al. 2018). As the MRE industry establishes commercial scale arrays, field programs will be needed to determine whether changes in systems will become detectable.

Adopting terminology from Whiting et al. (2023), changes in oceanographic systems can be categorized as nearfield effects, farfield effects, and secondary effects. Nearfield effects are physical changes within a few device lengths; farfield effects are physical changes at distances of more than a few device lengths that may affect large areas or entire waterbodies; and secondary effects are changes to ecological processes and species, resulting from the changes in the physical processes. Monitoring instruments presently in use can quantify nearfield changes like turbulence but are not fit for measuring farfield effects like changes in flow that are smaller than and masked by natural variability in the system (Robins et al. 2014; Wang & Yang 2017). Numerical models are used to predict farfield effects of large arrays. However, these models have generally not been validated with post-installation field data because no large arrays have yet been deployed. The exception to this may occur from the operation of OTEC plants, which move large amounts of water vertically. See Chapter 1 for more details on OTEC. Similarly, as large-scale salinity
gradients plants are developed, there will need to be some examination of potential oceanographic changes.

As the scale of tidal and wave deployment grows, it is anticipated that secondary effects may be characterized by observing the response of organisms and habitats to the physical changes in oceanographic conditions. Numerical models may provide predictions of what the secondary changes will be associated with larger physical changes.

To fill the remaining knowledge gaps around changes in oceanographic systems from MRE, the *2020 State of the Science* report, Whiting & Chang (2020) recommended further efforts be directed towards:

- Improving model validation: Creating more realistic models by increasing the use of high-quality bathymetry data and realistic device parameterization. Models can benefit from additional environmental monitoring as larger arrays are deployed;
- Assessing cumulative effects: Oceanographic systems regularly change in response to severe storms, multi-decadal weather patterns, and long-term climate shifts. Other anthropogenic pressures may also create change. Changes from MRE development should be viewed within the scale of this larger context; and
- Understanding environmental implications: Physical changes to the environment are particularly meaningful in the context of the resilience of marine populations and ecosystems to environmental pressures. Studies must compare changes from MRE with natural variability and other anthropogenic sources based on biogeochemical models, ecosystem models, and risk assessments.

3.5.1. ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Since the publication of the *2020 State of the Science* report (Copping & Hemery 2020), studies have proliferated on the hydrodynamic response from deployed tidal and wave devices that analyze array layout to optimize power production. However, fewer studies have focused on the potential effects of MRE on the nearfield, farfield, or secondary ecological processes. Recent tidal energy studies have primarily focused on characterizing the farfield effects of tidal arrays, with few studies translating the physical changes to secondary effects like sediment transport or changes in habitat extent or quality. In contrast, recent wave energy research has focused on the benefits of using WECs to protect areas threatened by coastal erosion, often using wave arrays of generally less than 30 devices.

TIDAL ENERGY

Edgerly & Ravens (2019) measured turbulence dissipation around a deployed turbine in the Tanana River, Alaska, US. Other studies have used numerical models to predict farfield effects, some informed by in situ current measurements (e.g., Rodriguez-Delgado et al. 2019; Blunden et al. 2020; Deng et al. 2020; Sánchez et al. 2022), in situ wave measurements (de Paula Kirinus et al., 2022), and flume experiments (Gotelli et al. 2019). Many studies focused on assessing farfield changes for MRE projects, where the results may be specific to a particular location as well as the size or configuration of the MRE technology to be deployed. For example, 5 to 200 turbines modeled in an archipelago showed that tidal flows were diverted away from the channel with turbines to a neighboring channel (Deng et al. 2020); 25 to 300 turbines modeled in a strait show a reduction in sediment transport (Auguste et al. 2022); and 30 turbines modeled in a channel leading to an estuary showed negligible changes to circulation and upwelling (Sánchez et al. 2022). Each study concluded that small tidal arrays do not change the system in a significant way compared to natural variability, but that large arrays have the potential to affect natural processes.

Studies have applied numerical models to determine the likelihood of tidal energy devices altering sediment transport. The results generally show that array layout determines the potential for asymmetrical modifications in flow, which may cause changes in sediment transport along the seabed and in nearshore areas (Blunden et al. 2020). Sediment transport and deposition were modeled over a ten-year period, showing a decrease in vertical circulation, the development of new lateral flows to move sediment, and an increase in bedload transport rates around the turbine due to divergence in flow (de Paula Kirinus et al. 2022). With reduced velocities resulting from flows around MRE arrays, the models demonstrated long-term sediment accumulation around the arrays (Ross et al. 2021). These model simulations show changes in sediment transport but do not provide information on the biological effects of the changes.

Additional field and modeling studies have examined secondary effects on marine organisms and habitats, based on direct observations from field data and numerical models. Monopiles in the water column were observed to enhance primary productivity in local areas by increasing vertical mixing and nutrient availability, similar to processes that occur in the wake of small islands ("island mass effect") (Haberlin et al. 2022). Aerial drone transects and hydroacoustic measurements were used to observe a seabird foraging hotspot in the wake of the deployed Strangford Lough turbine in the United Kingdom (Lieber et al. 2021). Imagery of the sea surface from an unmanned aerial vehicle showed that diving birds were associated with natural upwelling areas; these areas were shown to have increases in dissolved nutrients and biological activity including prey species for birds, as an example of a natural turbulence feature with an analogous wildlife response to tidal turbines (Slingsby et al. 2022). Vessel observations indicate that altering sandbank locations by the presence of tidal energy devices may impact the presence of sandeels, which act as prey for benthic foraging seabirds (Couto et al. 2022). These studies indicate that changes in oceanographic processes associated with the presence of individual turbines and their substructures may impact bird foraging hotspots, though it is unclear whether these changes will affect the survival or health of populations. Some of the key physical and environmental effects of tidal energy are illustrated in Figure 3.5.1.

WAVE ENERGY

Recent wave energy studies have focused on how changes to farfield effects potentially cause positive secondary effects by reducing erosion, flooding, and other effects of extreme events on coastlines. A WEC hull was designed specifically to improve coastal protection (Bergillos et al. 2019a). Other modeling studies examined the dual benefits of energy production and coastal protection (Moradi et al. 2022; Bergillos et al. 2019b), including coastal protection in mild wave climates (Rusu et al. 2021), winter storms (Onea et al. 2021), hurricanes (Ozkan et al. 2022), and in response to sea level rise (Rodriguez-Delgado et al. 2019). The studies that consider WECs for coastal protection are

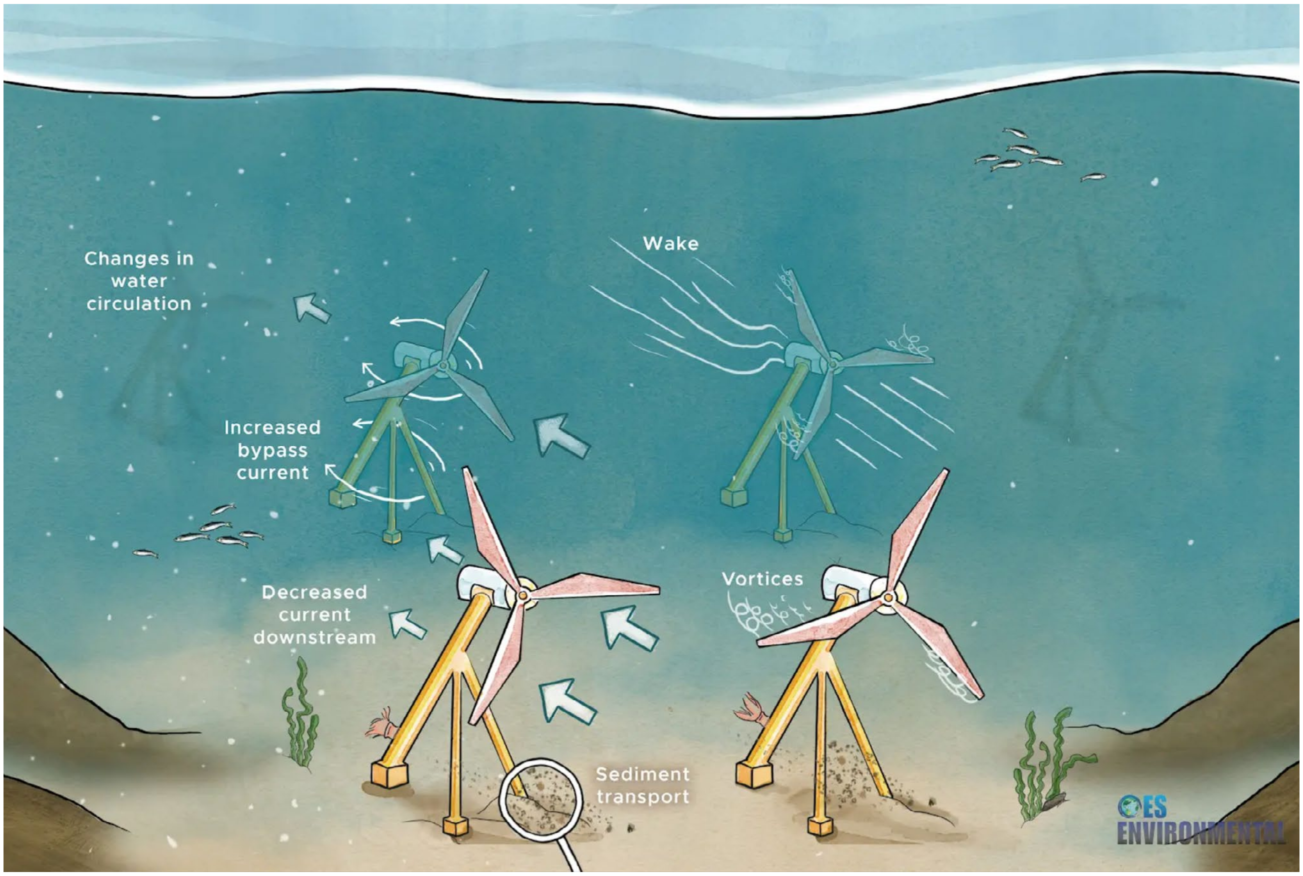


Figure 3.5.1. Schematic of a tidal energy array and the potential effects on hydrodynamics and sediment transport. (From Whiting et al. 2023)

located in southern Europe; it is not clear whether these measures will be effective on other types of coastlines. More research is needed on different archetypes of coastlines and embayment around the world to determine whether WECs can act as coastal protection for specific coastline geometries, sediment conditions, bathymetries, and wave climates.

Further studies explored the use of WECs for enhanced coastal protection by optimizing wave farm layouts. Closer spaced, denser arrays increase shoreline protection, according to modeling studies that varied the configuration of a small array at different distances from shore (Rijnsdorp et al. 2020). Bergillos et al. (2019c) used machine learning to assess wave farm layout to maximize dry beach surface as a metric of sediment accretion, a unique approach that needs validation. Distance to shore, inter-array configuration, wave direction, and seasonality are all factors that should be considered when gauging shoreline protection efficacy of WEC arrays. Some of the key physical and environmental effects of wave energy are illustrated in Figure 3.5.2.

OTEC

The return of large volumes of cold ocean water that has been used in an OTEC heat exchange process is the greatest potential environmental concern for this MRE technology (Coastal Response Research Center, 2009, 2010). The cold deep water will be brought to the surface at a temperature of about 4ºC, while surface and subsurface waters will be about 24–28ºC. After the heat exchange process, the cold water to be returned to the ocean is likely to be about 12–16ºC (Grandelli et al. 2012), still significantly colder than the ambient surface seawater. Standard OTEC designs include discharging the cold return water at an intermediate depth, generally below the thermocline, so that the water will sink rapidly to the depth where it matches the density of the ambient seawater. The depth at which the cold water is returned is determined through numerical modeling of the structure of the water column, validated with measurements of temperature, salinity, and depth—all standard oceanographic measurements. An open-source model for the cold-water return is under development at the

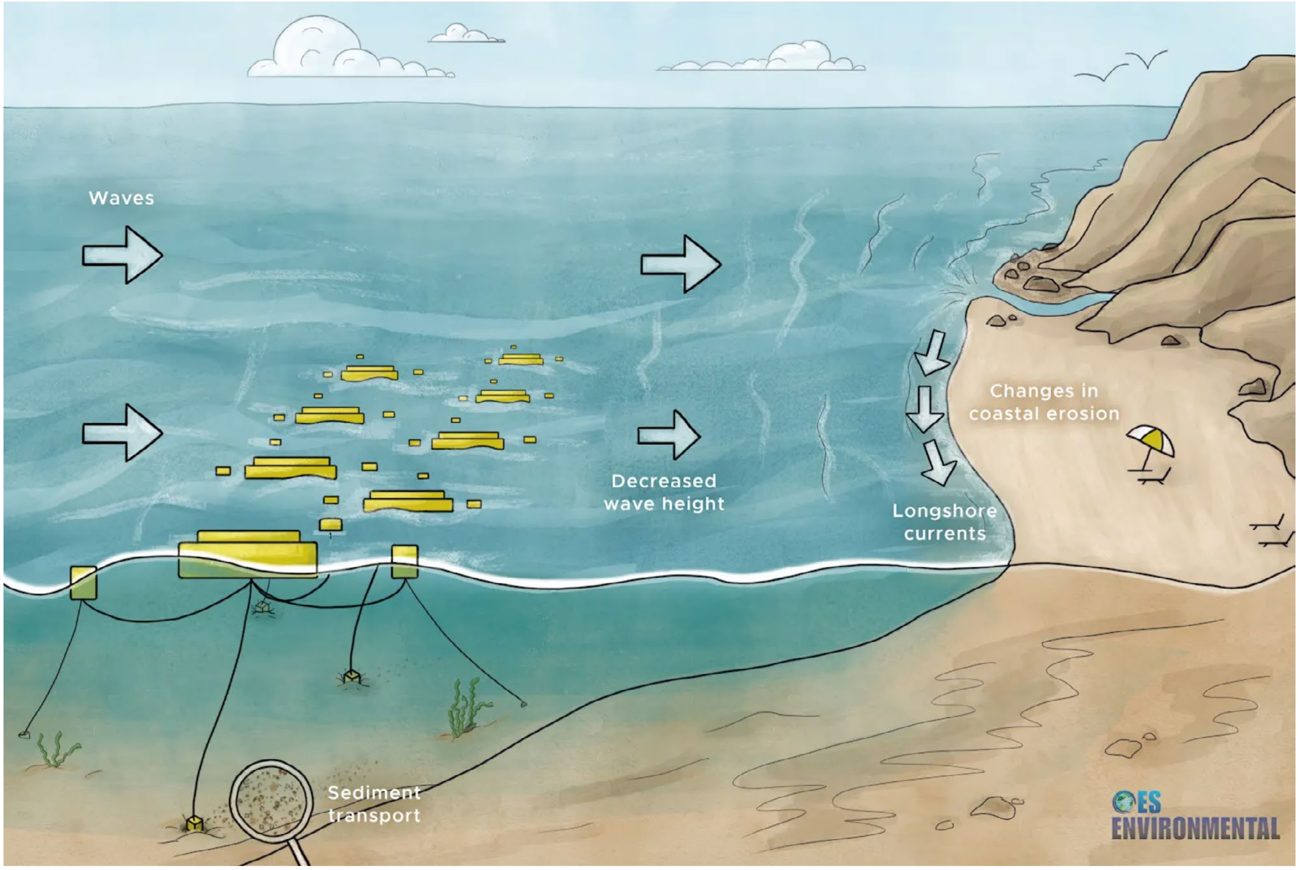


Figure 3.5.2. Schematic of a wave energy array and the potential effects on wave height, longshore currents, sediment transport, and coastal erosion. (From Whiting et al. 2023)

Pacific Northwest National Laboratory in the US and is likely to become widely used for siting and design of OTEC cold water discharge. If the cold water is returned at the correct depth to enable rapid sinking to the appropriate depths, there are likely to be no changes in the regional oceanography around OTEC plants, as they develop in the future.

SALINITY GRADIENTS

Salinity gradient power can only be generated where there is a significant difference in salinity between water bodies through an osmotic exchange process that creates concentrated seawater with approximately twice the salinity of the incoming seawater (Gallardo-Torres et al. 2012). Conditions that will allow salinity gradient power production apply exclusively to areas where large rivers empty directly into the ocean. While there may be some concerns around the need to dispose of the brine created during the process, perhaps causing nearfield increases in salinity, it is unlikely that the amount of additional salt water will affect large-scale oceanographic processes (Marin-Coria et al. 2021).

3.5.2. STATUS OF RISK RETIREMENT

Scientific literature indicates that changes to oceanographic systems from properly sited small tidal and wave deployments will be lower than those within the natural variability of the system, allowing the risk posed to the marine environment to be retired for small numbers of devices (one to six devices). OES-Environmental has developed a Changes in Oceanographic Systems Evidence Base listing the key research papers and monitoring reports that define what we understand about the effects from changes in oceanographic systems, and a Changes in Oceanographic Systems Guidance Document to evaluate the risk within a regulatory context.

Small deployments can be defined as removing less than 2% of the total theoretical undisturbed resource (IEC TC 114 Technical Specification 62600-201). Significant effects (larger than natural system variability) are unlikely to be measurable in the nearfield, including wake recovery (Edgerly & Ravens 2019) and scour (Lancaster et al. 2022). While there is little reason to engage in extensive monitoring programs for the effects of MRE devices for small deployments (Whiting et al. 2023), there is value in conducting proper site characterization studies to inform siting of projects as well as to help validate numerical models as the industry scales to larger arrays (ORJIP Ocean Energy, 2022c).

Changes in oceanographic processes associated with large arrays of tidal or wave devices have been examined by numerical models, but most lack post-installation validation due to insufficient data. Modeling large, unrealistic scenarios that are unlikely to be implemented can exacerbate unfounded concerns among stakeholders. Farfield changes caused by MRE deployments will be site-specific and will depend on the shape of the coastline, bathymetry, flow conditions, and wave climates. Once larger arrays are deployed, changes in flow or wave height must be measured against the backdrop of natural variability in the system, seasonality, and long-term climate shifts. Large-scale anthropogenic pressures must also be considered to understand the role that MRE might play in changing oceanographic systems.

Physical changes in the nearfield and farfield may influence biological and chemical secondary effects that may shape habitats, support individual marine organisms, and affect population survivability and health. Less is known about these effects, but research on natural phenomena may serve as proxies to understand potential effects (e.g., Haberlin et al. 2022).

There are insufficient numbers of OTEC or salinity gradient plants in the world around which to gather data to address risk retirement at this time.

3.5.3 RECOMMENDATIONS

There is little reason for regulators to require extensive collection of data around MRE devices for changes in oceanographic systems until larger tidal and wave arrays are deployed (Whiting et al. 2023). However, as larger arrays are commissioned, data collected around MRE devices can be used to validate models, to understand potential effects when sited in varied coastal geometries, and to compare changes against natural variability. Data collection and models should follow established international standards such as those published by the IEC TC 114, so that changes in oceanographic systems are evaluated consistently across the MRE device archetypes. Collaboration between developers and researchers will enable field data to inform future regulatory requirements at the array scale. As larger arrays are developed, there is a

need to consider how multiple arrays may influence one another, suggesting the need for a regional planning approach such as marine spatial planning (see Chapter 6) and cumulative impacts assessment (see Chapter 9), avoiding the disorder of ad hoc development that may be proposed by individual project developers (Waldman et al. 2019).

There is a continuing need to refine numerical models for MRE interactions with oceanographic systems; in addition to improving simulations of effects, models can be used to facilitate planning for field data collection. Models should be used to explore siting challenges unique to archipelagos, straits, estuaries, or other coastal geometries. Future efforts should leverage advancements in machine learning and compare performance against traditional conceptual and physics-based models for siting deployments, parameterizing device interactions with the flow, and quantifying farfield effects. Siting of future large arrays can be effectively directed from validated models, balancing power production optimization with potential environmental effects.

The potential for WECs to provide coastal protection should be investigated with a range of wave energy archetypes (e.g., point absorbers, overtopping devices, bottom-mounted WECs, etc.), along multiple coastline geometries with differing wave power regimes.

Long-term modeling studies are needed to match the temporal scale of changes to shorelines and sediment transport mechanisms, paired with the need for collection of validation data that covers multiple years of seasonal data (Ozkan et al. 2020).

As larger arrays are deployed, the importance of understanding the linkages between changes in oceanographic systems and secondary effects on habitats and populations will increase and should form the basis of new inquiries. Before large deployments are constructed, secondary effects can be explored by observing how habitats and organisms respond to natural variability, extreme events, and anthropogenic pressures.

Floating offshore wind and wave devices deployed at sea are likely to have similar effects on oceanographic systems. Similarly, fixed-bottom offshore wind and oil and gas platforms may be reasonable analogs for tidal turbine foundations and support structures. Collaboration among these industries will assist with understanding potential changes in oceanographic systems.

As deployments of OTEC and salinity gradient power plants advance, there is a need to develop standardized approaches to determine the potential risk to nearfield and farfield systems.

3.6.
ENTANGLEMENT RISK OF ANIMALS WITH MARINE RENEWABLE ENERGY MOORING LINES AND UNDERWATER CABLES

Author: Lysel Garavelli

To maintain their position on or below the surface, many MRE devices require mooring lines attached to the seabed. Underwater cables are used to carry power from MRE devices to an offshore substation or to connect devices within an array. These lines and cables are suspended in the water column and have the potential to become an entanglement hazard for marine animals (Figure 3.6.1). Entanglement occurs when an animal becomes directly entangled with mooring lines or cables. Species of concern for entanglement risk with MRE mooring lines or underwater cables are large marine mammals (e.g., migratory whales), large pelagic elasmobranchs (e.g., basking sharks), as well as other marine animals such as seabirds, sea turtles, and large fish.

Because of the slow development of the MRE industry worldwide and the lack of monitoring around these devices, the likelihood of entanglement can be inferred from other offshore industries. Unlike the unobserved occurrence of entanglement in MRE mooring lines and cables, entanglement of marine animals in fishing gear and other marine debris is widespread and relatively well understood (Hamilton & Baker 2019; National Marine Fisheries Service 2021). Potential consequences of entangled fishing gear on marine animals include negative effects on animal welfare (e.g., respiratory distress, injuries such as tissue damage, death), health status (e.g., effects on mobility, limited access to food), and populations associated with barriers to movements, migration, and reproduction (SEER U.S. Offshore Wind Synthesis of Environmental Effects Research 2022b).

As of 2020, available literature on the risk of entanglement to animals in the marine environment mostly focused on entanglement observations involving fishing gear and historical records of entanglement with submarine telecommunications cables (Garavelli 2020). Concerns were also raised about marine debris (e.g., lost fishing gear) getting caught in MRE systems

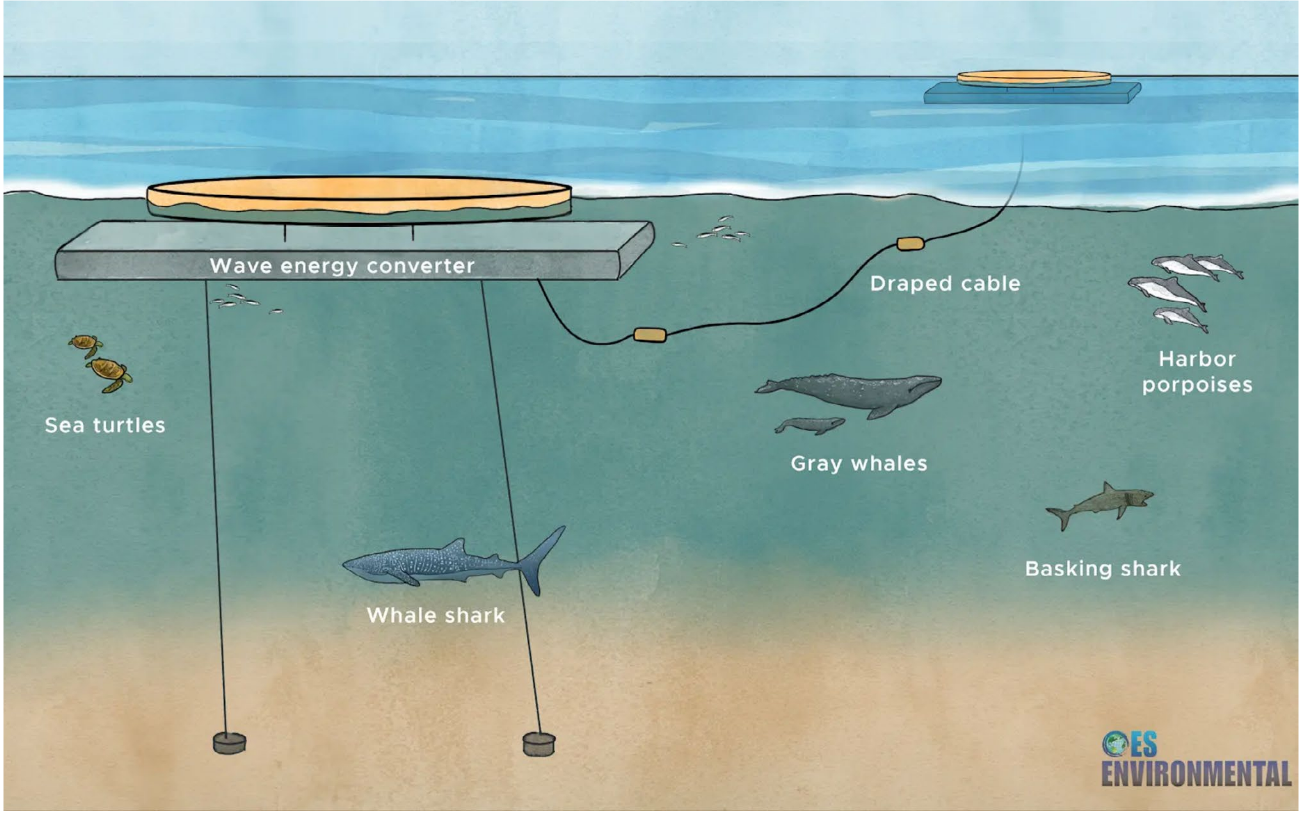


Figure 3.6.1. Schematic of wave energy converter mooring lines and intra-array cables that have a potential to pose entanglement risk to marine animals. (Illustration by Stephanie King)

and potentially affecting marine animals (also called secondary entanglement). Modeling studies predicted a low probability of entanglement, but empirical data were lacking to validate these models (Benjamins et al. 2014; Harnois et al. 2015). Studies found that the ability of echolocating marine mammals to use sound to communicate and to detect objects underwater will likely decrease the likelihood of entanglement. The risk of entanglement associated with MRE mooring lines and underwater cables has been suggested to be low as they are usually taut with no loose ends, and cannot form a loop, thus preventing the entanglement of marine animals (Benjamins et al. 2014). The potential consequences of entanglement were relatively unknown, and there remains a need to investigate how this risk may harm or injure specific marine animals. General recommendations to better understand the risk of entanglement associated with MRE devices included:

- combining modeling and field observations;
- identifying habitats and behavior or movement habits of large marine animals; and
- routinely monitoring mooring systems and inter-array cables.

3.6.1. ADDITIONAL KNOWLEDGE GAINED SINCE 2020

Recent information on the entanglement risk of marine animals associated with MRE devices is lacking and most of the knowledge is drawn from the fishing, aquaculture, and offshore wind industries. To date, no entanglements of marine animals with MRE systems have been observed and no evidence exists to show that such event has occurred (ORJIP Ocean Energy, 2022c). However, changes in behavior of marine animals around MRE devices, such as aggregation, may increase the probability of entanglement (ORJIP Ocean Energy 2022c).

In the commercial marine aquaculture industry, the risk of entanglement for marine animals has been described in Bath et al. (2023). In most countries with marine aquaculture development, the report of entanglement events is not mandatory, and data are scarce. Most of the documented entanglement events of marine animals with marine aquaculture gear have been for marine mammals (cetaceans, pinnipeds) with net pens used for finfish farming. Other entanglement events were documented for marine mammals with finfish cages, pearl oyster farm ropes, and mussel farm spat lines. In most of these entanglement reports, the outcome was fatal for the animal. Entanglement of sea turtles was also reported at shellfish farms. Seabirds and sharks are also at risk for entanglement with marine aquaculture gear, but no such events have been reported. Slack lines and netting materials used in marine aquaculture present the highest risk for entanglement of marine animals. Such materials are not used in the MRE industry.

In addition, multiple mooring lines and cables are unlikely to be close enough for an animal to be caught between them. In the oil and gas industry, entanglement with floating cables has never been reported (SEER U.S. Offshore Wind Synthesis of Environmental Effects Research 2022b). With the growing development of the offshore wind industry, recent studies have focused on the potential effects of underwater cables associated with floating wind turbines and no instances of entanglement have been reported. Given the large spatial scale of floating offshore wind turbines and the use of taut mooring lines and cables, it is also unlikely that a marine mammal would become entangled with such structures (Farr et al. 2021; Maxwell et al. 2022). Since 2020, there have been no reports of secondary entanglement of marine animals with derelict fishing gear and other marine debris getting caught in MRE systems.

The experience from the oil and gas and offshore wind industries suggests a low risk of entanglement to marine animals from mooring lines and cables associated with MRE devices. In the vast amount of ocean, the likelihood of fishing gear being snagged on MRE devices and associated secondary entanglement is also likely to be low. Notably, a large amount of fishing gear is being abandoned, lost, or discarded around the world yearly and the likelihood of this fishing gear becoming snagged on mooring lines and underwater cables would depend on their presence around MRE systems, their types, density in the water column, and susceptibility to being transported long distances (Macfadyen et al. 2009; Richardson et al. 2019).

Concerns around entanglement and its consequences on individuals and populations are mainly related to the theoretical potential negative effects on sensitive species. For example, in several parts of the world,

species with endangered or threatened regulatory status such as the North Atlantic right whale (*Eubalaena glacialis*) or various populations of the beluga whale (*Delphinapterus leucas*) in the US and Canada, are of concern. For such species, the entanglement of some individuals could drastically impact the overall population.

The conservation status of marine animals also increases regulatory and stakeholder concerns regarding the potential effects of entanglement from MRE systems. In Wales, stakeholders (regulators, industry, and environmental organizations) were recently surveyed to collect perspectives on the risk of entanglement for marine animals related to MRE systems (ORJIP Ocean Energy, 2022d). Compared to fish and seabirds, entanglement was perceived to be the greatest concern for marine mammals, although the likelihood of entanglement was unknown. Other factors that were noted to influence the perceived level of risk were the number and tension of mooring lines, and the presence of mid-water cables (e.g., for floating devices).

3.6.2. STATUS OF RISK RETIREMENT

OES-Environmental has developed an Entanglement Evidence Base listing the key research papers and monitoring reports that define what we understand about the risks of entanglement from MRE mooring lines and underwater cables, and an Entanglement Guidance Document to evaluate the risk within a general regulatory context.

Because mooring lines and underwater cables used in MRE systems do not have loose ends or have sufficient slack to create loops that could cause entanglement of marine animals, the risk of entanglement for a small number of devices (one to six devices) is considered low. The risk of entanglement may change when considering a large array of MRE devices with additional mooring lines and underwater cables, potentially increasing the likelihood of entanglement.

3.6.3. RECOMMENDATIONS

Although the risk of entanglement with MRE mooring lines and underwater cables is considered to be low, strategies can be applied to minimize the risk, particularly as the MRE industry moves toward large array deployments. At the siting stage, assessing the distribution of species of concern, their migration pathways, behavior, and habitats is crucial. In the absence of information, models can aid in predicting the entanglement rate based on species of concern and the configuration of lines and cables. If the risk of entanglement is proven to be likely, there will be a need to consider designing structures and configurations of mooring lines for MRE projects that will minimize the risk of entanglement. The use of taut mooring lines will decrease the likelihood of entanglement of marine animals.

Developing technologies to monitor the tension of lines and cables using load monitoring systems, failure detection, or entanglement detection should be considered for each MRE system. In addition, periodic visual inspection of mooring lines or underwater cables with instrumentation and remotely operated underwater vehicles is recommended and will help provide information on the presence of debris or derelict fishing gear snagged on MRE mooring lines and cables. Periodic inspection of mooring lines and cables may be necessary for the health of the MRE system, so the inspection for debris can be added to the work. Any debris detected could then be removed, preferably with the technology used for inspection. Other monitoring techniques could include the use of underwater cameras to observe any debris or animals caught in cables or mooring lines.

As the MRE industry advances and array-scale deployments occur, understanding the cumulative effects of MRE systems and other surrounding offshore activities will be needed (see Chapter 9), particularly for highly migratory species. Sharing data, information, and findings across offshore industries will continue to increase the understanding of entanglement risk.

3.7. DISPLACEMENT OF ANIMALS FROM MARINE RENEWABLE ENERGY DEVELOPMENT

Author: Lenaïg G. Hemery

Large arrays of MRE devices have the potential to trigger environmental effects not yet observable at the scale of single devices (Hasselman et al. 2023), such as the displacement of marine animals from their preferred or essential habitats or migratory routes (Hemery et al. 2024). Such effects could be particularly challenging for local populations of threatened or endangered species that have limited availability of alternative suitable habitat as marine areas face increasing pressure from human activities and the impacts of climate change. Improved comprehension of the risks and consequences of animal displacement resulting from deployment of MRE arrays is necessary; however, the current state of development of the MRE industry provides limited opportunities to understand the risks of and mechanisms that cause displacement due to the current absence of large-scale arrays.

Researchers studying displacement in the MRE context have used varying definitions depending on the specific animals or context of the study. Lacking a clear and consistent definition, investigations into the causes of displacement, species of concern, potential consequences, and methods of investigation by the international community are hampered (Hemery et al. 2024). In the context of MRE development, displacement has been referred to as the result of anthropogenic activities acting as disturbance and leading to habitat loss or a barrier effect, causing animals to avoid an area (Buenau et al. 2022; Copping et al. 2021b; Long, 2017; Onoufriou et al. 2021; Sparling et al. 2020a). Some studies postulated that displacement of fish or marine mammals would occur at spatiotemporal scales larger than those of collision avoidance when an animal approaches a turbine (Copping et al. 2021b; Onoufriou et al. 2021; Sparling et al. 2020a). While displacement is literally "the moving of something from its place or position" (Oxford Languages), the wind energy research community has often distinguished displacement from avoidance, barrier effects, or attraction (Marques et al. 2021; (SEER) U.S. Offshore Wind Synthesis of Environmental Effects Research, 2022a).

To clarify the causes, mechanisms, and consequences of displacement with respect to MRE, (Hemery et al. (2024) have proposed the following definition: "Displacement is the outcome of one of three mechanisms (i.e., attraction, avoidance, and exclusion) triggered by a receptor's response to one or more stressors acting as a disturbance, with various consequences at the individual through to population levels".

3.7.1. MECHANISMS OF DISPLACEMENT

The physical presence of MRE devices and/or associated infrastructure such as power export cables may create a disturbance strong enough to displace some animals. Further, stressors such as the movement of devices or parts of them that could represent collision risk, underwater noise and EMF emissions, and changes in habitats and hydrodynamics may all trigger a response from animals (Figure 3.7.1). Responses may be individual-, species-, and/or location-specific, and may include attraction, avoidance, or exclusion (Figure 3.7.2):

- Attraction is defined as the intentional movement of animals toward an area within or immediately adjacent to an MRE array (i.e., going toward);
- Avoidance is the intentional bypassing of an area with MRE devices to travel in the same general direction (i.e., going around); and
- Exclusion is the departure or movement away from the area, so the animal is no longer going in the initial direction (i.e., going away from), resulting in a barrier effect that prevents animals from passing through an MRE array and/or associated infrastructure.

The effects of displacement may result in outcomes across a range of spatial and temporal scales, from short-term to long-term (e.g., temporary effects that may change over time as animals habituate to the presence of the MRE array) to permanent displacement (e.g., a species never returns to a feeding habitat on the far side of an MRE array), with spatial scales dependent on the animal's home or migratory ranges and its sensitivity to the stressors (i.e., strength of the response and distance from the stressor).

Consequences of displacement may be observed from the individual to the population level and may include changes in survivability, bioenergetics, predation, competition, connectivity, productivity, and access to essential habitats (e.g., for feeding, breeding, rearing, traveling), as well as population failure if enough individuals are affected at a severe enough level (Sparling et al. 2020b). The consequences of displacement are likely to be greater for the species with higher vulnerability such as those with very small populations, those with a high degree of specialization, those at critical life stages such as molting or breeding, and those with limited access to suitable alternative habitat locally.

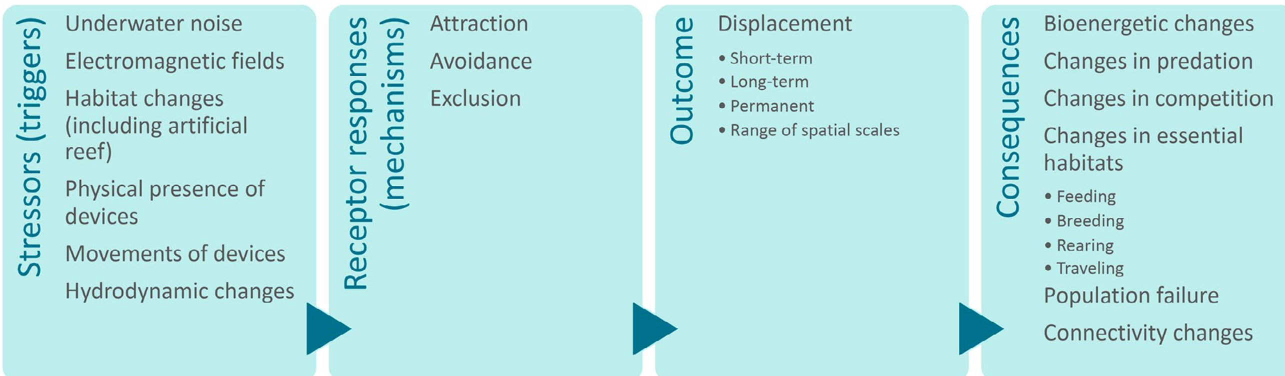


Figure 3.7.1. Displacement flow chart: displacement is the outcome of one of three mechanisms triggered by a receptor's response to stressors, with the potential for a range of consequences on marine animals that span from effects on the individual to effects on populations. (From Hemery et al. 2024)

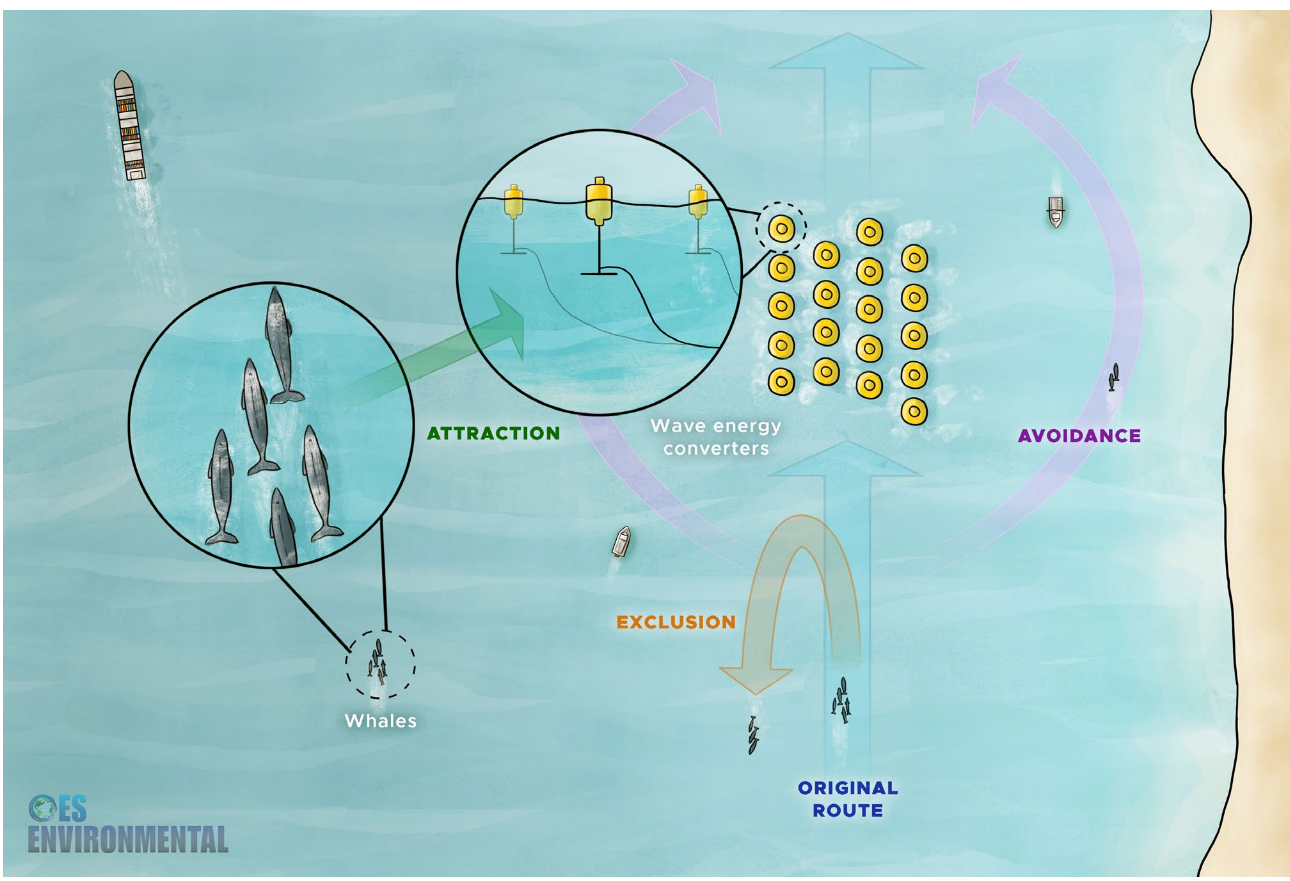


Figure 3.7.2. Mechanisms of displacement: upon encounter with an array of marine renewable energy converters, animals may exhibit no response, or exhibit an attraction, avoidance, or exclusion response that may result in their displacement from key habitats (e.g., foraging or breeding grounds). (From Hemery et al. 2024)

Displacement can affect marine species in different ways, based on their migration patterns, home range size and depth, maneuverability and swimming speed, gregariousness, etc. (Figure 3.7.3). Field observations remain essential in understanding causes, responses, and consequences of displacement for each species potentially affected. However, while many species may be affected, taking a functional approach allows for the range of species to be represented. Hypotheses can be generated for these functional groups from available literature gathered from other marine industries (Hemery et al. 2024):

- Large whales and large sharks: the physical presence of large arrays of MRE devices and associated infrastructure may create a disturbance for slow moving large species of whales (i.e., baleen whales) and sharks (e.g., basking shark); additionally, large whales may be sensitive to operation noise and vessel traffic associated with maintenance activities. Displacement could result in some bioenergetic losses if the animals are forced to prolong their migrations and/or feeding habitats become out of reach (Booth et al. 2013; Kraus et al. 2019), which could in turn affect reproductive success or survivorship.
- Small cetaceans: dolphins, porpoises, and orca may show behavioral responses to construction activities and operational noise generated by MRE devices. Impacts would most likely be site specific and result in temporary or longer term displacement (Gillespie et al. 2021; Palmer et al. 2021; Tollit et al. 2019).
- Pinnipeds: underwater noise from operational MRE devices and vessel traffic related to construction activities might cause temporary or longer term displacement of seals and sea lions (Savidge et al. 2014; Sparling et al. 2018); however, animals may quickly become habituated and return to the sites post-construction (Russell et al. 2016).
- Sirenians: manatees and dugong seem sensitive to vessel traffic and may be affected by construction activities (Hodgson & Marsh 2007); however, large MRE projects are unlikely to be developed in proximity to sirenians' nearshore suitable habitats.
- Sea turtles: while it is unknown whether MRE activities will lead to long-term displacement of sea turtles, temporary disturbance from construction noise may be observed in the form of area avoidance (Sullivan 2021).

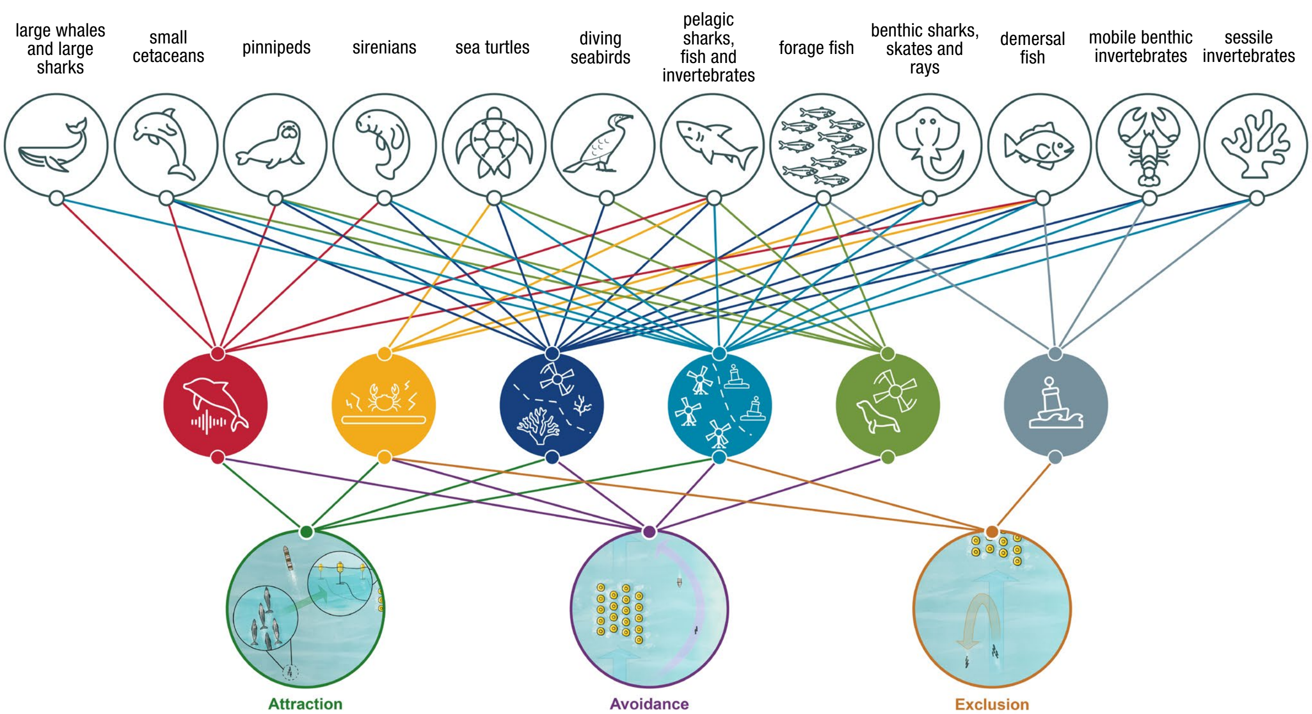


Figure 3.7.3. Potential stressors and responses for the different animal groups. Each of the three mechanisms for displacement is shown in the bottom row and connects to the six stressors, in the middle row (left to right: underwater noise, electromagnetic fields, habitat changes, physical presence of devices, movement of devices, and hydrodynamic changes). Each stressor connects to the range of marine animals that may be affected, in the top row. (Modified from Hemery et al. 2024)

- Diving seabirds: displacement of seabirds is most likely to be species- and site-specific, depending on time of year, activity of the seabirds, and a species' vulnerability to increased risk of collision, as well as food availability or attraction to new roosting habitats (Dierschke et al. 2016; Kelsey et al. 2018).
- Pelagic sharks, large pelagic fish and invertebrates: EMF from draped cables in between floating MRE devices within an array, as well as underwater noise, may attract or repulse species with specific sensitivity (Copping et al. 2021b; Snyder et al.2019); however, long-term consequences remain unknown.
- Forage fish: fish schools may avoid MRE project areas during construction activities or operation due to underwater noise, visual stimuli, or changes in flow patterns, while others may become attracted to new habitats and foraging sources (Staines et al. 2019; Williamson et al. 2019), but little is known about these effects.
- Benthic sharks, skates, and rays: MRE arrays may attract benthic elasmobranchs because of the EMFs generated by devices and/or cables, as well as the structures themselves providing new support for egg cases and habitat for prey (Maxwell et al. 2022; Snyder et al. 2019).
- Demersal fish: effects of displacement on demersal fish may be species-specific, with only some being attracted to the devices as they provide new habitats. Attraction may be more prevalent for larvae than adults as they may respond to acoustic and chemical cues; however, changes in hydrodynamics could displace some larvae from suitable habitats (Anderson et al. 2021; Langhamer 2012; van Berkel et al. 2020).
- Mobile benthic invertebrates: these animals may become attracted to arrays of MRE devices through acoustic cues or EMFs, and by the creation of the new artificial reef habitat provided by the devices and its associated infrastructure, leading to potential heightened exposure to EMF or underwater noise emissions (Anderson et al. 2021; Gill & Desender 2020; Langhamer 2016).
- Sessile invertebrates: larvae of sessile invertebrates may become attracted to MRE devices by acoustic cues and settle on the artificial structures before having a chance to reach natural habitats; this may increase connectivity between natural and artificial habitats, especially for invasive species (Adams et al. 2014; Dannheim et al. 2020; Lillis et al. 2015).

3.7.2. METHODS OF INVESTIGATION

Displacement of key marine animals associated with MRE development should be investigated with a combination of numerical models and field-based approaches to address remaining knowledge gaps (Hemery et al. 2024). While field observations have been limited in the absence of large arrays of MRE devices, those that have happened provide essential data to inform models. Numerical models or analytical frameworks can help assess risks and consequences of displacement:

- Agent-based models are used to represent the movement of animals around MRE devices and predict their spatial distribution over time (Grippo et al. 2020; Lake et al. 2015).
- Species distribution models are used to predict the probability of species occurrence based on habitat characteristics and physical features (Baker et al. 2020; Bangley et al. 2022; Lieber et al. 2018; Waggitt et al. 2016).
- The interim population consequences of disturbance framework and the population viability analysis could be used to assess population-level effects of disturbances (King et al. 2015; Sparling et al. 2020b).
- Dynamic energy budget models are used to predict the bioenergetic consequences of a disturbance at the individual to population levels (Harwood et al. 2020).

Field data are necessary upon which to develop and validate models. As much as possible, field data should be collected using reliable methods that do not interfere with animal behavior, such as:

- Land- and boat-based surveys that are used to record surface presence and habitat use of marine animals that are occasionally visible at/near the surface, such as marine mammals, seabirds, sea turtles, and some large fish (Lieber et al. 2019; Williamson et al. 2018).
- Aerial surveillance with drones that are used for observing animals with occasional presence at the sea surface (Lieber et al. 2019; Williamson et al. 2018; Slingsby et al. 2022).
- Passive acoustic underwater monitoring approaches that use hydrophones to target sound-producing animals like cetaceans and some fish species (Porskamp et al. 2015; Palmer et al. 2021; Wood et al. 2013; Gillespie et al. 2021, 2022).

- Active acoustic monitoring approaches that use scientific echosounders and multibeam sonars to detect animals, including fish and marine mammals (Gillespie et al. 2022, 2023; Staines et al. 2019; Williamson et al. 2021).
- Telemetry arrays that use acoustic or satellite tag detections that record location and (for certain models) depth at regular intervals to track three-dimensional movements of marine animals (Hastie et al. 2016; Onoufriou et al. 2021; Sanderson et al. 2023b).
- Underwater imagery/video surveys that are used to record underwater presence and habitat use, particularly for slow-moving animals (Broadhurst et al. 2014; Hemery et al. 2022b).
- Environmental DNA that can be used to record presence and habitat use by specific species or groups of species from water samples (Dahlgren et al. 2023).

Provided that the same methods are employed to collect meaningful baseline and post-installation data, results from such monitoring campaigns around arrays and in areas used by the species of concern should provide significant information to better understand the risks and consequences of animal displacement from MRE development. However, careful attention should be given to experimental designs to collect data that will provide sufficient statistical power to detect change over time and understand mechanisms of displacement.

3.7.3. STATUS OF RISK RETIREMENT AND KNOWLEDGE GAPS

Animal displacement is a stressor-receptor interaction that is not considered to be an issue for small MRE projects (one to six devices) and, in such, has seen little investigation to date due to the absence of large-scale arrays of MRE devices; therefore, it is not suitable for risk retirement. However, as larger projects are planned, it is important that the MRE community understands the mechanisms and significance of animal displacement around MRE projects in order to consent large arrays, having confidently assessed the potential for significant displacement effects, with the possible implementation of mitigation measures yet to be determined. Remaining knowledge gaps include information on the distribution and behavior of marine animals of concern, potential effects of specific MRE technologies and certain stressors, and interactions between animals and the technologies, as well as cumulative effects of displacement from multiple developments.

While existing legislation in some jurisdictions could conceivably be used to address displacement, presently there is no explicit understanding of this risk among the MRE regulatory or research community and fit for purpose regulations are needed that will ensure that the risk of displacement does not harm marine species. Table 3.7.1 lists these remaining knowledge gaps, along with the stakeholder groups in a position to best support gathering the information, and the necessary timelines for addressing them. Investigating any or all of these gaps will significantly advance our understanding of the risks and consequences of animal displacement around MRE arrays.

3.7.4. RECOMMENDATIONS

To progress the investigation and understanding of the risks of animal displacement around wave and tidal energy arrays, Hemery et al. (2024) have provided a definition of displacement and its mechanisms and consequences for various animal functional groups. This stressor-receptor interaction is unlikely to be a priority concern until the deployment of large MRE arrays. However, it is important to:

- Understand the potential mechanisms that cause displacement and the possible consequences to marine animals;
- Generate realistic models of such consequences, in combination with stressor-specific models;
- Identify how to best monitor and mitigate these changes; and
- Initiate monitoring as soon as larger arrays are deployed.

The remaining knowledge gaps highlighted in Table 3.7.1 should help the MRE regulatory and scientific communities prepare themselves for mitigating, observing, measuring, and characterizing animal displacement around MRE arrays to prevent irreversible consequences. The timing is right to begin discussions within the MRE community on how to investigate and address the risk of displacement, ahead of large-scale arrays being planned and consented.

Table 3.7.1. Remaining knowledge gaps to be addressed to fully understand the risks and consequences of animal displacement around marine renewable energy development, along with stakeholders best positioned to support the work, and a suggested timeline for addressing these gaps.

Remaining Knowledge Gaps	Best-positioned stakeholders	Timeline
Specific to Marine Animal Displacement:		
Species likely to be affected by displacement	Regulators / Researchers	Short term
Species behaviors and habitat use	Regulators / Resource Agencies / Researchers	Medium term
Stressors, mechanisms, and consequences of displacement relevant to each species of concern	Regulators / Resource Agencies / Researchers	Medium term
Differences in behaviors and biological rates among life stages, individuals, or populations within a species	Regulators / Resource Agencies / Researchers	Medium term
Spatiotemporal scales relevant to each species and life stage	Researchers	Short term
Consequences of displacement from individuals to population and species levels	Regulators / Resource Agencies / Researchers	Medium term
Understanding displacement in the context of climate change and other cumulative effects	Regulators / Resource Agencies / Researchers	Long term
Specific to Marine Energy Technologies:		
Array configurations (e.g., size, geometry, spatial coverage, cable route) and/or device types likely to cause displacement	Researchers	Short term
Scaling of underwater noise and/or EMF emissions to arrays	Researchers / Developers	Short term
Surrogate marine and/or terrestrial activities that inform displacement	Regulators	Short term
Specific to Monitoring Displacement:		
Commercial-off-the-shelf monitoring technologies most suitable for each species and necessary adaptation to different sites and marine energy technologies	Researchers	Short term
Necessary modifications to existing observation technologies versus development of new technologies	Researchers	Short term
Spatiotemporal scales for monitoring surveys for each species and marine energy technology, especially at large-array project level	Regulators / Researchers	Short term
Monitoring displacement in the context of climate change and other cumulative effects	Researchers	Long term
Specific to the Regulatory Context:		
Existing specific national and international regulations or statutes applicable to displacement of marine animals (related to marine energy and/or other sectors)	Regulators	Short term
Common regulations already protecting species and populations that displacement could fall into	Regulators	Short term
Any actions regarding displacement that may be required by law or recommended	Regulators	Medium term

Note: More detail is available in Hemery et al. (2024).

3.8. CONCLUSION OF STRESSOR-RECEPTOR INTERACTIONS

Each subchapter has described our understanding of stressor-receptor interactions from MRE devices and systems, providing the most up-to-date assessments of the state of knowledge, based on published research, data gleaned from monitoring around deployed devices, modeling simulations, and the expert opinions of the many researchers who collaborate and coordinate work in this area, around the world.

The most concerning stressor-receptor interaction associated with tidal and riverine turbines is that of collision risk. The concerns continue to be focused on marine mammals, fish, diving seabirds, and in some locations, sea turtles, that might be injured or killed by colliding with moving blades. These concerns drive the single most difficult aspects of consenting these devices. Effects of underwater noise and EMFs continue to be raised in consenting approvals and requirements for post-installation monitoring, but the effects of these emissions are becoming fairly well understood. Changes in benthic and pelagic habitats are important aspects of moving towards consenting, but well-sited small arrays or single devices are generally understood to have little unique effect at the ocean scale. In the absence of dedicated monitoring, entanglement of large marine animals remains a theoretical risk that is unlikely to slow the consenting of MRE devices in the near future. Similarly, the level of potential changes in oceanographic systems from small numbers of devices is not a problem for consenting small deployments. OTEC systems provide a different challenge for consenting due to the potential oceanographic effects. Displacement remains a potential future consenting issue as larger deployments and commercial arrays are realized.

The state of knowledge of environmental effects of MRE development is changing rapidly, as more studies are completed, and more deployed devices are accompanied by planned post-installation monitoring programs. However, there remain relatively few devices operating at any one time around the world, even fewer small arrays, and as of this time, no large arrays, around which monitoring data collection and research experiments can be carried out. For the moment, the research community and the MRE industry who depend on them for answers to support consenting must continue to rely on laboratory studies, numerical models, and limited field studies.

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Suggested citation:

Garavelli, L., Hemery, L. G., Rose, D. J., Farr, H., Whiting, J. M., and Copping, A. E. 2024. Marine Renewable Energy: Stressor-Receptor Interactions. In L. Garavelli, A.E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 26-102). doi:10.2172/2438589

Section C

HUMAN DIMENSIONS OF MARINE RENEWABLE ENERGY

CHAPTER 4.0
SOCIAL AND ECONOMIC EFFECTS OF MARINE RENEWABLE ENERGY

CHAPTER 5.0
STAKEHOLDER ENGAGEMENT FOR MARINE RENEWABLE ENERGY

4.0

Social and Economic Effects of Marine Renewable Energy

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While the 2024 *State of the Science* report primarily focuses on the interactions between marine renewable energy (MRE) and the environment, to fully account for the effects of MRE development, the social and economic aspects must also be considered. Incorporating how societal elements are altered related to the construction, operation, and maintenance of MRE projects and how MRE development may affect communities on a local, regional, and/or national scale is necessary to understand the suite of effects from the industry.

Economic aspects that may be affected by MRE may include employment, supply chains, and existing industries, while social aspects may include health, safety and well-being, culture, governance, gender equality and social inclusion, as well as infrastructure and services (Freeman 2020; Karytsas et al. 2020; Kerr et al. 2014; Vanclay et al. 2015) (Figure 4.1). Nearly any effect can be considered to have a social component if it has been identified as important to a specific group of people (Soukissian et al. 2023). Though often discussed together, social and economic effects should be considered separately as they vary in definition, level and extent of impact, data collection requirements, and methods and scale of assessments. In many cases, social and economic effects are closely coupled with environmental effects, and it is important to consider these factors together to holistically understand the effects from MRE on a particular community or region, especially in the wider context of sustainable development (Dalton et al. 2015; Martínez et al. 2021; Mendoza et al. 2019; Niquil et al. 2021; Richardson 2021).

The MRE industry has unique opportunities to deploy at varying scales and in areas where traditional renewable energy is not best suited or feasible (e.g., solar energy in the Arctic), providing access to social and economic benefits and a source of clean energy that would otherwise be unavailable (Regeneris Consulting Ltd. & Welsh Economy Research Unit, Cardiff Business School 2013; Smart & Noonan 2018). Developing countries and islands or remote coastal communities in particular have been in focus for renewable energy transitions broadly (Kallis et al. 2021), and for MRE specifically (Adesanya et al. 2020; Borges Posterari & Waseda 2022; Fadzil et al. 2022; Felix et al. 2019; Hernández-Fontes et al. 2020; Ramachandran et al. 2020, 2021). However, these new contexts, coupled with the nascent status of the industry, make predicting the social and economic effects of a specific MRE project difficult (Bonar et al. 2015). Compounding this, data from existing or past projects are often unavailable or not collected or analyzed at all. The limited data, and therefore overall research, make it challenging to identify MRE-specific social and economic effects. As such, there remains a need to increase understanding of these effects through research and data collection to foster benefits and minimize or avoid negative impacts from MRE developments.

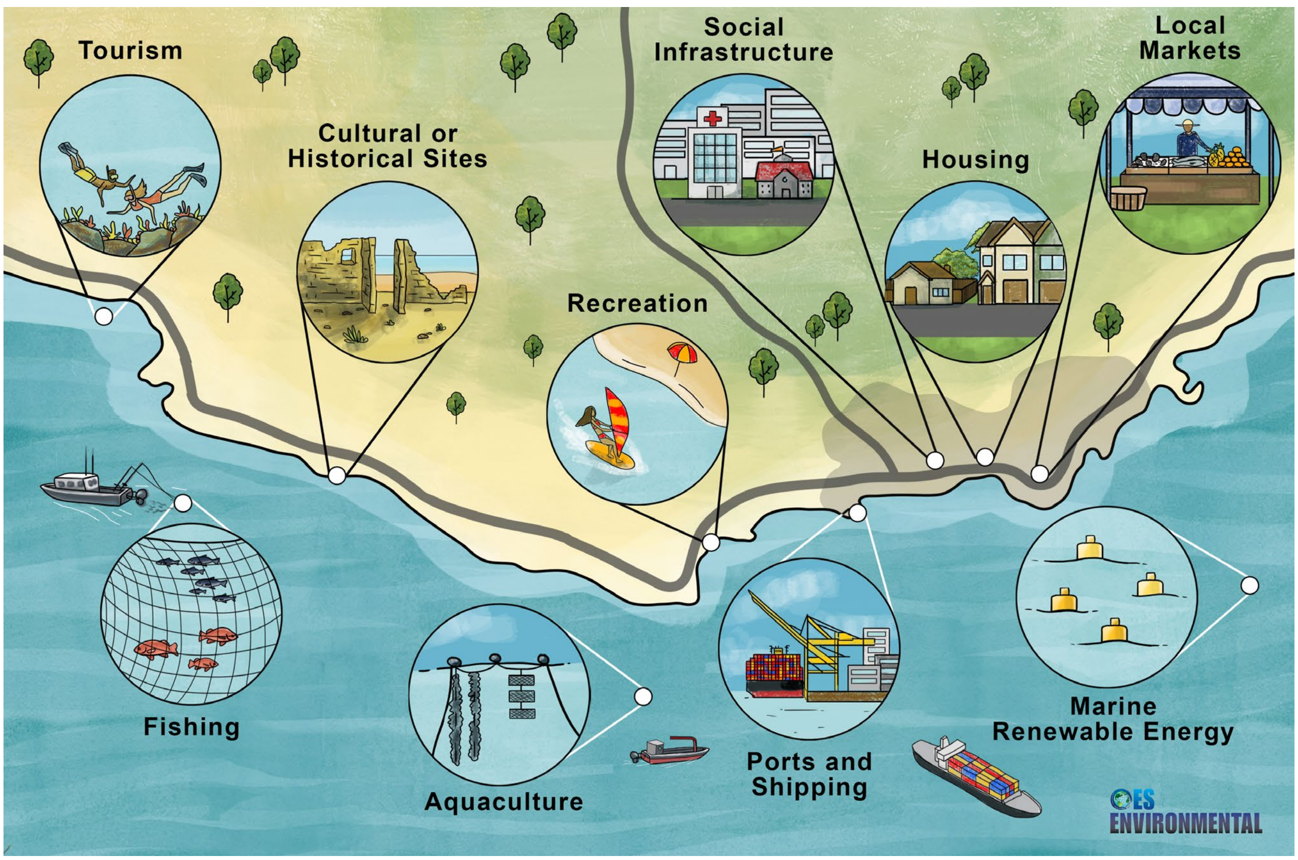


Figure 4.1. Examples of coastal and marine industries and community aspects that may experience social and economic effects from marine renewable energy. (Illustration by Stephanie King)

This becomes increasingly important as the MRE industry scales up to larger-scale or commercial arrays, as effects may be limited at the scale of demonstration or single device projects but are likely to increase with commercial-scale projects (see Chapter 9). It is also particularly important to expand knowledge as the sector begins to explore opportunities in off-grid markets, often involving remote and island communities that are already being impacted by climate change and need access to reliable, affordable, and sustainable energy.

Social and economic assessments are typically included within environmental assessments as part of consenting processes for MRE projects, as the effects are often closely linked, or during strategic planning processes (Freeman 2020; Wright 2014). When most successful, these include stakeholder engagement activities to inform MRE planning and development including identifying effects, siting projects, distributing benefits, minimizing negative impacts, and building relationships with community members. It is important for MRE projects to achieve social license as well as required regulatory consents. Stakeholder engagement for MRE is important, but because social and economic effects research does not address questions of stakeholder or community participation and engagement this is discussed more thoroughly in Chapter 5.

The objectives of this chapter are to:

- Review the findings of the *2020 State of the Science* chapter on Social and Economic Data Collection for MRE (Freeman 2020);
- Review the social and economic effects documented for MRE from the literature;
- Review the approaches for assessing social and economic effects specific to MRE, including an update to the good practices for data collection and information on the regulatory context within various Ocean Energy System (OES)-Environmental countries from the *2020 State of the Science* report;
- Present case studies of data collection and social and economic effects for MRE planning and development; and
- Offer recommendations for future work to build a deeper understanding of social and economic effects from MRE.

This chapter does not address the economic feasibility of MRE or discuss techno-economic optimization approaches. While some of these particular tools and approaches are used in predicting social or economic effects or informing decisions, they are not the focus of this review.

4.1. PREVIOUS OES-ENVIRONMENTAL WORK ON SOCIAL AND ECONOMIC EFFECTS

To date, OES-Environmental's efforts on social and economic effects from MRE have focused on data collection, aimed at supporting consenting processes (Freeman 2020). Topics that have been addressed include requirements in OES countries and responsibility for collecting such data; additional needs to increase understanding and good practices for data collection (Copping et al. 2019); and distinctions between strategic-level (local, national, or regional objectives implemented by government, agencies, marine planning entities, or other relevant organizations) and project-level (local or project objectives implemented by a project developer, local agency, or local organization) data collection (Figure 4.2).

Overall, it has been difficult to identify and assess the social and economic effects from MRE as there is a deficiency in regulatory guidance on data collection and analysis (an issue not unique to MRE), data—both baseline and long-term monitoring—collected to date and research carried out around MRE projects, and standardization in approaches used for MRE (Dalton et al. 2015; Ocean Energy Systems & ORJIP Ocean Energy 2017). OES-Environmental developed good practices for social and economic data collection to address some of these challenges (Copping et al. 2019), which have been updated in Section 4.3.

To advance understanding of social and economic effects from MRE, Freeman (2020) identified the need for:

- Social and economic data to be collected consistently and over a sufficient duration to facilitate comparison and to identify long-term effects;
- Tools and databases to help identify social and economic indicators;

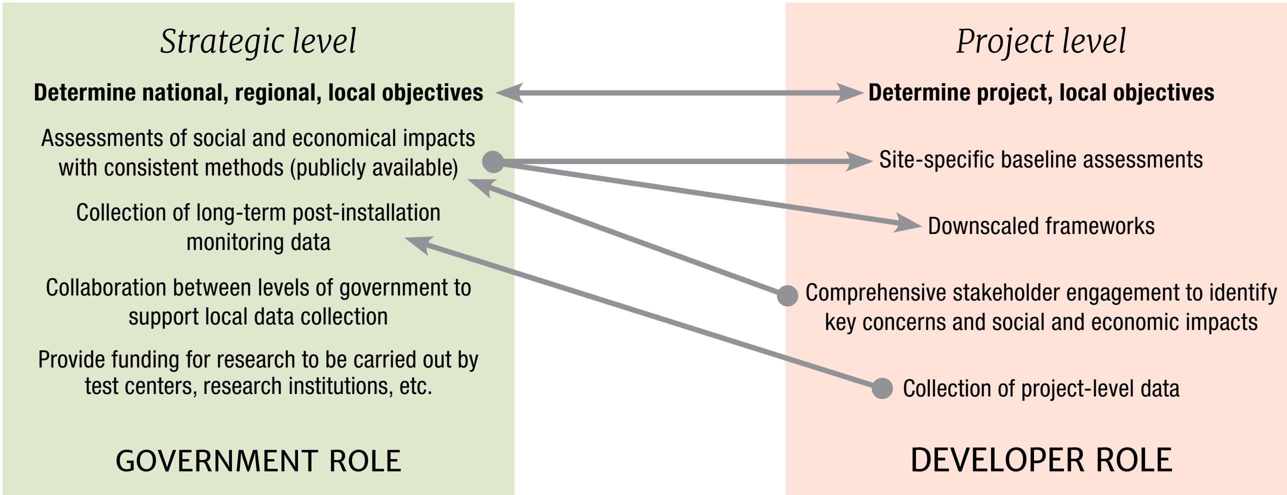


Figure 4.2. Responsibilities of governments and developers in collecting social and economic data. Updated from Freeman (2020).

- Templates, including specific questions to be answered, to guide data collection and analyses;
- Meaningful stakeholder engagement;
- Incentivizing data collection and provision of public access to those data; and
- Requirements and consenting processes to be proportionate to the project size and potential impact and to be flexible, particularly while building knowledge on social and economic effects.

4.2. SOCIAL AND ECONOMIC EFFECTS DOCUMENTED FOR MRE

Positive, negative, and neutral social and economic effects have been both speculated upon and documented for MRE (Bonar et al. 2015; Freeman 2020). MRE developments have the potential to stimulate local and/or regional economic development in the short- or long-term, including by generating revenue and employment opportunities directly (Jimenez et al. 2015; Lavidas 2019; Regeneris Consulting Ltd. & Welsh Economy Research Unit, Cardiff Business School 2013) or indirectly; for instance, through tourism opportunities (Callejas-Jiménez et al. 2021; DeSanti 2020) or via the associated MRE supply chain (Soukissian et al. 2023). MRE may also provide new industrial or commercial opportunities for groups that have not received benefits from historical marine industries (Bax et al. 2022; Kabir et al. 2022; Lacey-Barnacle et al. 2020). Social benefits may also accrue, such as enhancing or creating energy security and resilience or contributing to the development of needed infrastructure. Negative impacts could include exclusion of traditional marine users from an area, or changes to the aesthetics of a place (Axon 2022; Bailey et al. 2011; de Groot & Bailey 2016; Howell 2019; McLachlan 2009). Social and economic effects can also be tightly linked to environmental effects of projects (Niquil et al. 2021), especially in coastal and other ocean-dependent communities or regions with a history of reliance or culture based on marine resources or ocean-based activities (Richardson 2021).

Assessing social and economic effects can be a requirement during consenting processes and should occur from the outset of project planning and development, just as environmental effects are examined. The social and economic effects from MRE are important to consider for strategic planning efforts, for developers hoping to site a project, for project owners who will manage a project through its lifetime, and for communities and marine users who stand to gain or lose. Social and economic effects, or the public's anticipation of them relative to community values, can pose non-technological barriers to the development of the MRE industry (Apolonia et al. 2021; Colmenares-Quintero et al. 2020). Such concerns and perceptions must be examined for individual projects to assure public satisfaction and project success.

To address these challenges, the international social science literature around renewable energy in general and for MRE specifically has been emphasizing equity, energy and environmental justice, and just energy transitions (Caballero et al. 2023; Carley & Konisky 2020; Cisneros-Montemayor et al. 2021; Hanke et al. 2021; Levenda et al. 2021; Withouck et al. 2023). This includes aspects of recognition justice (i.e., who is involved) (Bacchiocchi et al. 2022; Berka & Dreyfus 2021; Dwyer & Bidwell 2019), procedural justice (i.e., who participates in decision-making) (Klok et al. 2023; Knudsen et al. 2015; Walker & Baxter 2017), and distributional justice (i.e., who benefits vs. who is impacted) (Burdon et al. 2022; Cisneros-Montemayor et al. 2022; Kerr et al. 2017; Mueller & Brooks 2020). Emphasizing the importance of justice—and associated community values that can help understand justice, and its effects more broadly—in research and throughout planning and development of an MRE project may allow the industry to avoid some of the past injustices that have been perpetuated through energy transitions and build a new legacy for clean energy that considers these important aspects of equity and justice (Dutta et al. 2023; Fouquet 2010; Hoffman et al, 2021; Kouloumpis & Yan 2021; Lockwood et al. 2017; Ponce Oliva et al. 2024).

The following sections describe social and economic considerations and highlight effects that have been documented or hypothesized for MRE, organized by those who may be affected or involved throughout planning, development, and operation. While it is ideal to address social and economic effects separately, in practice this can be challenging particularly as some effects may overlap (e.g., visual effects, resilience, well-being, etc.). Due to the limited information available on MRE-specific social and economic effects, research from adjacent industries (particularly offshore wind) is included. The following sections focus mainly on documented social and economic effects research and remaining knowledge gaps; more information on the involvement and engagement of these groups as stakeholders can be found in Chapter 5.

4.2.1. FISHERIES

Fishers are often considered one of the primary groups affected by any new activities in the ocean (Bonar et al. 2015). Many different species of fish, shellfish, and algae may be targeted through commercial, recreational, subsistence, or Indigenous fisheries and most are subject to regulations depending on the type of fishery, gear types, sustainability of the harvest, and management structure. Fisheries globally are facing a range of pressures due to climate change including affecting fishing grounds, declining stocks, historic overfishing and mismanagement, constraining management rules (e.g., to allow for rebuilding stocks or to assure sustainability), the increasing complexity of navigating global markets and supply chains, and new ocean uses competing for space (Harper et al. 2023; Hilborn et al. 2021; Johnson & Welch 2009; Lam et al. 2020; Pauly et al. 2002; Pauly & Zeller 2016).

In many coastal communities, target species provide the main sources of local protein and micronutrients and fishing is often a multi-generational livelihood; thus any proposal for new activity in the ocean becomes deeply connected to food, community health, livelihoods, and security (Papadopoulou & Vlachou 2022; Qu 2021; Steins et al. 2021). Non-fishers in a community may also be invested in pressures on a fishery or the legally protected rights of fishers (Dreyer et al. 2019). Knowledge from fishers has contributed to and played a key role in marine spatial planning, ocean zoning, and siting of offshore structures and activities, including processes to establish marine protected areas, offshore wind farms, and MRE (Ashley et al. 2018; Bakker et al. 2019; Campbell 2015; Jia et al. 2022; Kyriazi et al. 2016; Letschert et al. 2021; Oregon State University 2013; Yates et al. 2015).

Fishers have significant experience engaging in many decision-making processes and are considered *definitive stakeholders* with legitimacy, power, and urgency (Johnson et al. 2015; Trouillet et al. 2019), though there can be strong power differentials, with small-scale fishers having much less influence than industrialized fishers. Individual or community fisher perspectives on MRE are highly variable based on the anticipated effects of MRE, surrounding community context, dependency on the fishery resource, culture and traditions, export markets, and connection to tourism or other income sources related to a healthy fishery (Willis-Norton et al. 2024). Common concerns related to fisheries include fear of displacement from typical or historical fishing areas, loss of income or livelihood due to displacement or reduced catches, and uncertainty around the potential effects of MRE on harvested species and long-term ecosystem health.

SPATIAL DISPLACEMENT

The inability to harvest in a previously utilized location is a primary concern of fishers, as exclusion areas may be established around MRE projects during installation and operation for safety, security, and optimal operations (Stelzenmüller et al. 2022; Xoubanova & Lawrence 2022). Exclusion or no-take zones have been suggested to function similar to a marine protected area, with potential positive impacts on fished populations. This effect has yet to be demonstrated for MRE (Bender et al. 2021), though is well-documented for other exclusion areas such as marine protected areas and offshore wind farms (Alexander et al. 2016; Breen et al. 2015; Coates et al. 2016; Hemery 2020; Raoux et al. 2017). Spatial displacement can result in a loss of income due to potentially reduced catches, and even the loss of livelihood if a fishery is no longer profitable due to new spatial restrictions within a preferred fish habitat, or increased travel time and effort to harvest an equivalent catch (Alexander et al. 2013). The effects of spatial displacement have been studied at several MRE locations and were found to vary significantly by gear type (Campbell 2015; Stelzenmüller et al. 2022), typical usage of the area (for example, in some places high tidal energy areas are not typically used for fishing (Kularathna et al. 2019)), and ability of fishers to adapt to new spatial constraints (Bastardie et al. 2015). This makes it important to represent multiple fisheries and gear types in planning and siting decisions for MRE, in order to assure full consideration of both the magnitude and the distribution of effects (Campbell 2015; Cohen et al. 2019; de Groot et al. 2014; Reilly et al. 2016; Withouck et al. 2023). In addition, it is important to consider that fisheries data is often commercially or culturally sensitive, and fishers may be reluctant to share prime fishing locations or catch data in a public setting (Calderwood et al. 2023; Davis & Hanich 2022), therefore fisheries data that is available and used in planning and siting should be assessed for accuracy. Participatory approaches that consider this sensitivity and go beyond mere consultation or data gathering are recommended (see Chapter 5), especially as conflicts over access to ocean space are expected to increase over time (Stelzenmüller et al. 2020).

MITIGATION

In the event of unavoidable or unforeseen impacts on fisher livelihoods, there are options to mitigate the effects of displacement and/or create compensatory benefits for those affected (de Groot et al. 2014). These negotiations typically take place before impacts occur (see PacWave South case study, Section 4.4) and require agreement from multiple parties to assure satisfactory outcomes (de Groot et al. 2014; Kularathna et al. 2019; Sando et al. 2022). In some cases, these agreements enable the co-existence of a fishery with MRE where it would not otherwise be possible. Mitigation can include financial compensation or non-monetary options, which might include collection of additional oceanographic data for the fishery, construction of artificial reefs or other fishery support structures, discounted electricity, using profits from energy generation to take management measures to aid coexistence (Hasuike & Inagaki 2021), or agreements to ensure local labor or fishing vessels are used in construction, operation, and maintenance of MRE projects (Kularathna et al. 2019). The preferences of fishers on benefits can vary based on gear type, scale of operations, current financial stability, or involvement in other community businesses (Kularathna et al. 2019).

ENVIRONMENTAL EFFECTS

Even if a fishery is not displaced by an MRE project, there may still be concerns about the effect that the device(s) or their construction could have on target species, prey species, habitats, or other ecosystem aspects, all of which are linked to the sustainability and profitability of the fishery. These environmental effects of MRE are discussed in more detail in other sections of this report, particularly for changes in habitat and collision risk (see Chapter 3). Research is needed to understand the positive and negative effects of MRE on target species to be able to predict impacts on the fishery as a whole (Willis-Norton et al. 2024; Xoubanova & Lawrence 2022), and should consider additional sources of mortality or injury (e.g., cumulative effects) as well as positive effects (Nogues et al. 2023). Such research and monitoring are needed at a strategic level to coordinate existing fisheries management across regions that may be experiencing cumulative effects of MRE or other development activities, as fish are not constrained by jurisdictional boundaries (Stelzenmüller et al. 2020, 2022; Xoubanova & Lawrence 2022).

EFFECTS ON AQUACULTURE

Marine-based aquaculture—the rearing of finfish, shellfish, or algae in coastal or offshore areas—may also experience some of the same effects from MRE as fisheries, particularly competition for space in a crowded ocean. Few negative effects on aquaculture from MRE have been identified. Most research in this area has focused on identifying potential synergies between aquaculture and renewable energy, including multi-use platforms (Abhinav et al. 2020) or co-location of MRE to power aquaculture operations (Freeman et al. 2022). Recent research has focused on the relevancy of offshore wind for aquaculture due to the fixed nature of platforms and equipment used (Gimpel et al. 2015; Schupp et al. 2019; Weiss et al. 2018); though coastal community perceptions vary and concerns remain (Billing et al. 2022; Steins et al. 2021). Aquaculture has been identified as a potential end-user and market for MRE, with opportunities for co-location, but much of the current work is still in the theory, exploratory, and design phases (Branch et al. 2023; Freeman et al. 2022; Garavelli et al. 2022; Silva et al. 2018; Yue et al. 2023).

4.2.2. OTHER MARITIME INDUSTRIES

Existing industries that may directly interact with MRE in ocean and coastal regions include port facilities and infrastructure; the supply chain covering all aspects of MRE device design and production, development, deployment, and decommissioning; the MRE workforce; and other marine industries such as shipping, navigation, security, defense, and dredge and disposal. Potential synergies between these maritime industries and MRE exist. For example, MRE could supply power to military and defense activities (Maurer et al. 2020), to ocean observation or navigation systems, or to ships to achieve vessel electrification as part of low-carbon energy solutions (LiVecchi et al. 2019). Another opportunity is the development of hybrid renewable energy systems, such as combined MRE and offshore wind or solar platforms (Ayub et al. 2023; Gubesch et al. 2023; Jiang et al. 2022; McTiernan & Sharman 2020; Solomin et al. 2021).

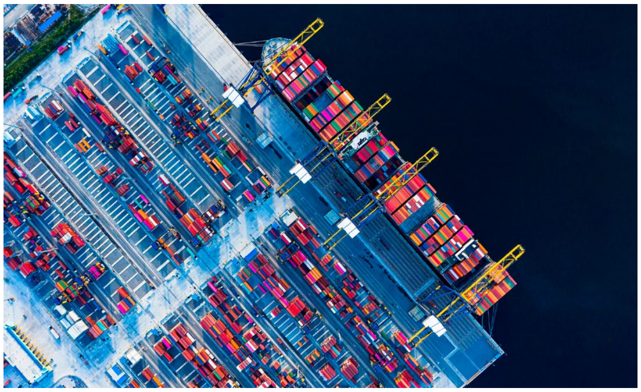
Key to the blue economy is managing the suite of maritime industries via sustainable development while protecting ocean ecosystems and resources and strengthening social and community aspects (Bethel et al. 2021; Cisneros-Montemayor et al. 2021, 2022; Lee et al. 2020; World Bank & United Nations Department of Economic and Social Affairs 2017). As the marine space becomes increasingly congested and as the MRE industry scales up to arrays and commercial-scale deployments, the need for comprehensive spatial planning and other tools like spatial or navigational risk assessments and buffer zones will become crucial to carry out negotiations between maritime industries and minimize potential effects (Mehdi et al. 2018; Naus et al. 2021).

There is limited research on the interaction between or effects of MRE on these maritime industries. The majority of the available information comes from reports on the European MRE industry that focus on economic opportunities such as job creation and training, bolstering the supply chain, and assessing development of the sector (Marine Energy Wales 2021, 2022; Ruiz-Minguela et al. 2022; Soukissian et al. 2023). Other applicable research typically focuses on offshore wind and shipping or navigational safety due to concerns of increased risk for ships and vessels and methods to better assess or mitigate risk (Mehdi et al. 2020; Naus et al. 2021; Rawson & Brito 2022). Available research on two key aspects for MRE development, ports and the supply chain, are highlighted in the following sections.

PORTS

Ports, connected to waterways and ranging in size and capabilities, are the center of marine transport networks and provide infrastructure and facilities for a variety of marine-based activities such as cargo, passenger transport, container transport, military operations, fishing, offshore wind, and MRE (Roa Perera et al. 2013; Sheikholeslami & Tabbakhpour Langeroodi 2024). Ports are a necessity for any marine industry and provide critical infrastructure for most populated coastal communities. For MRE this can include the need for deep water ports for manufacturing and deployment, service ports for pre-installation and device assembly, ongoing operations and maintenance, and facilities for dockside repair (Pacific Energy Ventures 2011). In the offshore wind industry, much attention and research has been afforded to the development of port infrastructure, required upgrades, and potential effects of this development. The MRE industry has not increased in scale to the same extent as offshore wind; consequently, there is a current gap in research on effects of MRE on ports. While there may be some synergies between port infrastructure needs for offshore wind and utility-scale, grid-connected MRE developments, for most MRE applications the requirements will be quite different in terms of scale, capacity, and location due to the smaller footprint of MRE developments. There are examples from MRE—particularly around test centers and areas ripe for MRE development—where investments in port infrastructure have been undertaken to support the industry and attract developers (Marine Energy Wales 2021).

Similar to the potential opportunity of co-locating MRE and aquaculture or other maritime industries, there is an opportunity for MRE to be integrated into ports to provide power to the port itself or to the grid (Bellon De Chassy 2020; Cascajo et al. 2019; Kandiyil 2022). Eco Wave Power is an example of a wave energy device designed to be integrated into port breakwaters, with several projects currently in operation (Eco Wave Power 2022). Port use and/or integration for MRE must be planned and executed carefully as MRE, like other new and developing marine-based industries, can either help diversify activities and increase job opportunities (Akbari et al. 2017) or has the potential to take away port space from existing industries leading to other impacts such as reduced workforce or long-term, union employment (Weig & Schultz-Zehden 2019).



SUPPLY CHAIN

The MRE supply chain includes operations (assembly, deployment, decommissioning), manufacturing (specialized and heavy manufacturing such as design of components and sub-systems, shipbuilding, heavy metal work), services (maintenance, research, project management, administration, legal, finance, etc.), and infrastructure (ports, harbors, test centers) (Ruiz-Minguela et al. 2022; Soukissian et al. 2023). Some components of the supply chain are location-dependent and must be carried out on site or where available ports/manufacturing equipment exists, while others may be carried out in areas adjacent to or surrounding an MRE project. Effects on the supply chain from MRE are typically quantified based on economic indicators (e.g., job creation, investments, etc.) and include indirect indicators, such as purchases or expenditures in businesses and industries that occur secondary to the development and operation of an MRE project (Bianchi & Fernandez 2024).

MRE has the potential to create opportunities for businesses and industries within the supply chain and the wider community, and provide economic benefits to coastal regions, local communities, and areas surrounding MRE development (Cochrane et al. 2021; Marine Energy Wales 2021; Norwood et al. 2023; Ruiz-Minguela et al. 2022) (see Orkney case study, Section 4.4). However, this will require investments to enhance local and regional supply chains that provide services needed for MRE (Cochrane et al. 2021; Marine Energy Wales 2021, 2022). A developing MRE supply chain may benefit from areas where workers have transferable trades or skills from adjacent industries such as offshore wind (Marine Energy Wales 2021). Otherwise, investments may need to be supported by governments at this early industry stage and can include funds for developing manufacturing services, expansion or customization of port infrastructure, and commissioning of specialized vessels. Such investments can foster growth in local companies and increase the visibility of local areas while increasing confidence in the MRE sector (Marine Energy Wales 2022; Ruiz-Minguela et al. 2022). Showing economic benefits from MRE can highlight business opportunities and attract new businesses throughout the supply chain to a particular area or region (Bianchi & Fernandez 2024). In some locations, regional coordination or the forming of clusters within the supply chain for MRE has occurred, which can also support development (Marine Energy Wales 2021; Ruiz-Minguela et al. 2022; Soukissian et al. 2020). As the MRE industry scales up, there are likely to be additional development opportunities (e.g., fabrication) that will necessitate increasing the capability and scale of the supply chain (Soukissian et al. 2023). For areas where MRE resources exist, but where the industry has yet to deploy or where government investments are limited, favorable policies will be needed to enhance the supply chain and prepare for MRE (Kasharjanto et al. 2023).

There is limited published research and few metrics that describe local economic effects of MRE on supply chains. Available information does not identify economic effects by phase of MRE development, clarify which industries are affected, or allow for comparison across the MRE sector (Bianchi & Fernandez 2024). Understanding of economic effects of MRE on the supply chain will require developing common and transparent methods to estimate them.

4.2.3. WORKFORCE

Specific skills are needed to support MRE and supply chain industries including engineering, device development, offshore operations and maintenance, research, environmental monitoring, resource assessment, legal services, public relations, stakeholder engagement, administration, finance, and more. A key economic benefit of MRE is job creation, particularly skilled work focused in coastal regions (Lavidas 2019; Marine Energy Wales 2021; Soukissian et al. 2023). Employment can be directly related to work carried out for MRE; indirectly created through association with activities, goods, and services that stem from MRE such as the supply chain; or induced by direct and indirect worker spending (Lavidas 2019). Assessments of job creation typically focus on direct and indirect jobs as induced employment can be hard to quantify and interpret (Ruiz-Minguela et al. 2022).

As the MRE industry continues to grow, employment opportunities have increased (Farrell et al. 2020; Marine Energy Wales 2022; Soukissian et al. 2023), and the need for additional workforce has been identified, especially for highly skilled workers (Soukissian et al. 2023). MRE has the potential to create jobs for professionals and skilled maritime workers with experience from adjacent industries who may want to move into a new industry or need alternative employment (e.g., from displaced fisheries, shipping, oil and gas), thereby offering security and resilience within the broader workforce (Marine Energy Wales 2021; Norwood et al. 2023; Soukissian et al. 2023). Training programs and skills development specific to MRE are needed and can be achieved through government, MRE sector and industry, educators and educational institutions, and researchers working together. These entities can offer training, industry apprenticeships, upskilling programs, resources, and school curricula that introduce MRE and allow for skills development (Marine Energy Wales 2021; Ruiz-Minguela et al. 2022; Soukissian et al. 2023) (see Chapter 7).

With a developing industry and supply chain comes the need to accommodate the required workforce. Housing, accommodations, health services, recreation, and more will be necessary to support the influx of workers (Kazimierczuk et al. 2023). This is likely to directly affect coastal communities for any scale of MRE project and will be especially important to evaluate for remote and coastal communities that are already resource-limited and may not have adequate services to support current populations (Quirapas & Taeihagh 2021). While opportunities for local businesses to develop or grow may arise, this can also put pressure on local services without proper management and investment (Kallis et al. 2021).

As with other aspects of maritime industries, there is an overall lack of information related to job creation and the workforce from MRE (Lavidas 2019), and the available studies vary widely in their reported job creation potential (Farrell et al. 2020; Ruiz-Minguela et al. 2022). Developing a better understanding of the direct and indirect jobs resulting from MRE will help identify economic benefits, plan for and manage potential effects, and allow for regions across the globe to compare and share lessons learned from MRE and supply-chain workforce development.

4.2.4. INDIGENOUS COMMUNITIES

Indigenous communities must be included when considering MRE development and its potential social and economic effects. Indigenous peoples—identified by various terms around the world such as First Nations, Tribal Nations, Native American, Alaskan Native, Inuit, Māori, Polynesian, and more—are stewards and custodians of the land and water since time immemorial and have lived in sync with the environment for subsistence use, cultural and historical activities, commercial resource use, and environmental management and monitoring (United Nations 2007; United Nations Permanent Forum on Indigenous Issues 2015). Indigenous groups are not mere stakeholders but are sovereign nations and rights holders; in most nations there is a history of colonialism and often disregard for such rights as well as a legacy of extractive industries occurring on Indigenous lands, all of which have led to the marginalization of Indigenous people worldwide and resulting distrust of governments and industry (Bacchiocchi et al. 2022; Duff et al. 2020; Lyons et al. 2023; Richardson et al. 2022). This section does not comprehensively address legal regimes (recognized groups, formal consultation, etc.) related to Indigenous rights as they are complex and vary across countries and jurisdictions (e.g., United States federally recognized Tribes and Alaska Natives, Australia Aboriginal Land Rights Act 1976 and Native Title Act 1993, Canada Constitution Act 1982, etc.) (Kerr et al. 2015; Lyons et al. 2023). These legal regimes and differing country contexts play a role in the recognition and inclusion of Indigenous communities related to MRE development. Instead, the focus of this section is on Indigenous communities and peoples and the associated social and economic effects in relation to MRE.

Often Indigenous people reside in coastal and/or remote locations and many such communities depend on fossil fuels for energy production. Energy security and self-sufficiency as well as community development and economic opportunities are often drivers for Indigenous communities transitioning to more reliable and renewable energy sources (Richardson et al. 2022). Indigenous communities that are located near the ocean or rivers with viable marine energy resources may be well suited for obtaining power from MRE.

Each Indigenous group is unique and has specific values, culture, and history; therefore, assessing potential impacts is best done at the MRE project-level and/or community scale which may occur beyond geographic boundaries of a project, and should be tailored to the specific context of each group (Richardson et al. 2022). MRE developments have the potential to affect many aspects of Indigenous lives and cultures such as traditional uses and harvesting rights, customary practices, cultural values and well-being, relationship to the environment, historic sites, access, livelihoods, employment, social programs and infrastructure, businesses, and more (Lyons et al. 2023; Richardson et al. 2022). When siting MRE projects, subsistence or cultural areas of use as well as culturally and historically significant areas should be identified and not considered for development. It should be noted that these may include culturally sensitive data and information that requires relationship- and trust-building (Richardson 2021).

The literature on Indigenous groups and MRE or analogous industries (blue economy, offshore wind, etc.) has identified several recommendations to work toward comprehensive assessments of social and economic effects on Indigenous groups and enhancing benefits while reducing negative impacts. First, assessments must include geographical, historical, social, and cultural contexts and values of Indigenous groups (Lyons et al. 2023). Indigenous frameworks should be used to identify and assess impacts and consider options, including that outcomes and benefits from MRE projects are defined by Indigenous groups. Indigenous knowledge should also be incorporated during project design and siting, data collection, and assessments of potential social and economic effects (Duff et al. 2020; Richardson, 2021). Further, development should be sustainable, inclusive, and equitable; language from the UN Declaration on the Rights of Indigenous Peoples (United Nations 2007) and its principles of Free, Prior, and Informed Consent (Food and Agriculture Organization of the United Nations 2016) should be used. Partnerships can be developed that support Indigenous groups' autonomy to assess impacts and management or development options, that provide benefits and limit risks and costs, and achieve cultural license to operate (Hunter et al. 2023). There is also a need to make data and resources (technical reports and academic literature) accessible and available to communities to inform understanding of MRE; to provide funding to support involvement of Indigenous communities and to increase capacity to seek additional financing and navigate project development processes; and to offer learning opportunities and employment, including the ability to be self-sufficient regarding maintaining and fixing technologies (which is particularly crucial for remote locations) (Richardson 2021). And importantly, renewable energy industries need to promote energy justice throughout these processes to avoid continuing and exacerbating historical injustices, including from other energy industries, that have impacted Indigenous communities (Bacchiocchi et al. 2022; Bennett et al. 2021; Kerr et al. 2015; Lacey-Barnacle et al. 2020).

4.2.5. COASTAL COMMUNITIES

Coastal communities refer to groups of people living at the intersection between the land and the sea; approximately 10% of the world's population live 10 m above sea level and 40% live within 100 km of the coastline (McGranahan et al. 2007; United Nations Office of Legal Affairs 2021). Coastal communities are diverse and have complex and unique relationships with and strong ties to the coast. This includes the marine environment, marine resources, and the seascape, and related social and economic infrastructure that depend on these aspects of the coast. Fishing, tourism, recreation, and cultural and historical practices are some of the main activities linked to coastal environments. The potential effects from MRE will depend on the unique characteristics and identity of each community and their social, economic, cultural, and historical values (Frolova et al. 2022; Howell 2019) (see EnFAIT case study in Section 4.4). Research on coastal communities has focused on local perceptions of social and economic effects and

attitudes—particularly related to support or opposition to renewable energy development. Factors that influence perceptions are impacts on tangible (local benefits or impact on tourism, property value, or the environment) or intangible (impact on personal and community well-being, place attachment including historical, cultural, and natural value) aspects (Johansen 2019). Anticipated effects, based on community perceptions and perspectives, cannot be disentangled from actual social and economic effects as they will drive attitudes; therefore, it is necessary for any MRE project to understand and address both actual and anticipated effects.

Studies of MRE found that factors influencing perceptions and attitudes on social and economic effects of MRE are mainly related to place attachment and use of a place (Hooper et al. 2020; Howell 2019; Kazimierczuk et al. 2023). Perceptions are also formed based on communities' and individuals' values, potential environmental effects (Hooper et al. 2020), local community context, willingness to accept change, distribution of benefits (Ponce Oliva et al. 2024), scale of the proposed project, trust in decision-makers and developers, visual impacts (Norwood et al. 2023), participation in planning processes, and fairness and transparency (Howell 2019). A variety of factors have been found to impact coastal community perceptions. One study identified age as a significant demographic factor related to opposition to tidal energy (Hooper et al. 2020). Another found attitudes on wave energy varied by gender, race, education, and political ideology as well as by use of the coast; overall there was more agreement for statements about benefits (e.g., energy independence, economic, job) than about risks (e.g., fishing, recreation, visual, environment) (Boudet et al. 2020). Support for renewable energy projects can also be based on trade-offs, particularly creating a balance between reducing negative local impacts and increasing positive local benefits (or providing too few benefits) (Bell et al. 2013; Howell 2019).

Research on perspectives of coastal communities regarding other coastal industries is useful to employ because social and economic research specific to MRE is limited. Additionally, factors affecting coastal communities' response to and perceptions of the effects from wind energy projects tend to be similar for MRE (Howell 2019). Coastal communities where engagement related to offshore wind development has occurred over time have seen changes in opinions more favorable for offshore wind as the community becomes accustomed to the sector (Frolova et al. 2022; Soukissian et al. 2020). An area that has not been studied much for attitudes regarding MRE is the difference in perspectives between permanent residents and second homeowners within a community. For offshore wind, Johansen (2019) found permanent residents to be more positive/supportive and focused on long-term impacts, and second homeowners to be less supportive and focused on impacts to use of local resources (beaches, etc.). There is a relatively large body of research from offshore wind, but the social and economic effects from these much larger-scale wind farms may not be directly applicable to MRE. While these findings are useful to inform how coastal communities may perceive MRE, there are differences (such as MRE developments typically being smaller, more nearshore, etc.) that are important, particularly when it comes to visual aspects. Howell (2019) found that there was more support from the local community for MRE than wind projects due to limited visual impacts, but also noted the importance of recognizing visual impacts from onshore infrastructure associated with MRE.

To address effects on communities, MRE projects have the potential to be advantageous through community benefit schemes, or other methods to mitigate potential risks and impacts. These approaches will need to address and acknowledge the diversity of each community (Johansen 2019), ensure that benefits are distributed fairly to the communities associated with an MRE development (Frolova et al. 2022), and create long-term benefits rather than only short-lived positive effects. Community ownership is one example where communities invest in a project and directly receive funds from energy production. This allows for community-led solutions to managing and distributing these funds to support the local community, which in turn aids equity between project developers and the communities where projects are located (Aquatera Ltd 2021). Community benefits from projects is a complex topic and includes the challenge of defining the local community and distributing decision-making power around benefits (Soukissian et al. 2023). Additional research is needed to better understand how to implement community benefits for MRE. Ideally, communities should be included and engaged from the outset, which will help discussion about planning, siting, and community benefits (see Chapter 5). The uniqueness and diversity of coastal communities mean that planning, data collection, research, and engagement are best carried out on a project-level scale and on a community-by-community basis to understand the complexities, intricacies, and structure or organization of these communities (Frolova et al. 2022; Soukissian et al. 2023). Respect should be placed on the existing social, economic, and cultural aspects of a community, and the existing and historical relationships to the marine environment and resources throughout all MRE project phases (Frolova et al. 2022).

4.2.6. TOURISM

Coastal tourism, an increasingly popular sector of tourism for travelers, involves recreational activities occurring near or within the marine environment (European Commission et al. 2023). In coastal areas, tourism opportunities often directly depend on a healthy ocean environment to provide activities and experiences such as fishing, boating, wildlife viewing, and clean water for swimming and other recreational activities. Tourism may be affected by the development of MRE due to spatial displacement or changes in the overall visual aesthetic of a place, and the effects may vary based on the typical visitors and activities in a particular area. Perspectives on MRE vary by tourism operators and place-specific attributes (Callejas-Jiménez et al. 2021; DeSanti 2020) and by perceived environmental effects (Marin-Coria et al. 2021). Additional tourism opportunities may be generated by the presence of a new MRE technology, development, or visitor facility, though this may not be a long-term driver of increased tourism as the novelty wears off (Carr-Harris & Lang 2019; Smythe et al. 2020). There is also potential for MRE to facilitate ecotourism, either alone or combined with other renewable energies to provide typical tourism activities with a lower climate impact (Ben Jebli et al. 2019).

Limited research has been carried out demonstrating or measuring effects of MRE on tourism, in part due to few devices in the water and public opportunities for viewing or visiting. More research has been undertaken for offshore wind farms (Carr-Harris & Lang 2019; Machado & de Andrés 2023; Westerberg et al. 2015), though the visual effects of offshore wind turbines are much more striking than MRE devices and can have polarizing effects (Smythe et al. 2020).

4.2.7. CONSERVATION

Many areas of the ocean and coastal zone are designated for conservation purposes, to protect rare or important species, habitats, or historically or culturally important areas (Klein et al. 2010). These designations may vary based on the jurisdiction and conservation goals (e.g., marine protected areas, sanctuaries, parks, conservation zones, no-take zones, or reserves). The restrictions or level of protection within each area varies by the management approach and legal protections in place. Fishing and other extractive or disruptive activities, such as mining, drilling, or dredging, are often excluded in these areas, though other activities such as non-consumptive recreation may be allowed (e.g., surfing, diving, snorkeling, or use of powered or non-powered personal watercraft). MRE developments are typically excluded from these areas, although there have been some discussions about compatible uses of space in particular instances, especially in already busy ocean areas (Jhan et al. 2022; Steins et al. 2021). Most research to date has focused on opportunities for spatial planning to co-locate different ocean uses considering tradeoffs between industries, with the preservation of key species, biodiversity, or ecosystem processes as an implicit goal (Jia et al. 2022; Markantonatou et al. 2021; Van der Biest et al. 2020; Virtanen et al. 2022; Yates et al. 2015).

There may be additional concerns about the siting of MRE developments near conservation areas due to potential environmental effects across a broad spatial distribution. The conservation value of a species or habitat may also vary according to the power of influence of stakeholders who defend or represent it (Fofack-Garcia et al. 2023). These concerns can vary based on the specific interests of individuals and organizations. Including managers of existing or planned conservation areas and their stakeholders (Bonnevie et al. 2023; Friedrich et al. 2020), fisheries (Campbell 2015), environmental non-governmental organizations (Brooker et al. 2019), and other conservation interests, such as archaeological, historical, or cultural societies (Bailey & Flemming 2008; Pollard et al. 2014), is necessary in the planning process for MRE projects to site appropriately, identify social and economic effects, and avoid conflicts.

4.2.8. ENERGY END-USERS

All those who consume or utilize energy in a particular location have the potential to be affected by MRE. A new MRE project could influence the availability (quantity and timing) and reliability of power and the cost of electricity and other energy services, depending on how the electricity is owned or distributed (Hernández-Fontes et al. 2020; Shao et al. 2022). These effects could be perceived as positive or negative, in part depending on the specific aspects of a project and power provided, as well as local views around clean energy and emission reductions if communities are able to switch power consumption away from carbon-intensive energy (Jiang & Khattak 2023; Richardson et al. 2022; Smart & Noonan 2018). Additional infrastructure installations or upgrades may be needed as part of MRE development and incorporating MRE into transmission and distribution systems, which may also have effects further inland and along transmission corridors (IRENA 2022; Marine Energy Council National Hydropower Association 2021).

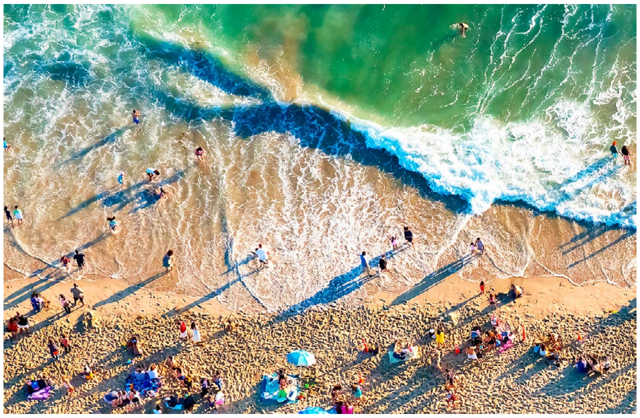
An important consideration is the export of energy produced, particularly who it will benefit or negatively impact. A main concern related to energy end-users is when local communities where projects are sited—and therefore effects from a project are mainly experienced—do not receive the benefit of energy produced (de Groot & Bailey 2016; Linnerud et al. 2022). This creates disdain as these communities experience the local effects from a project, but the energy is instead exported inland, to larger metropolitan areas, or even across regional or national boundaries. Alternatively, when energy produced from a project is provided to the local community this can create an important benefit, particularly when reductions in the cost of electricity are anticipated or materialize (de Groot & Bailey 2016; Firestone et al. 2009). Further, using produced energy for the local electric supply can help enhance energy security, which is particularly important for island or remote communities, and was found by one study on offshore wind to be a main predictor of support (Devine-Wright & Wiersma 2020).

In many cases, MRE may be used to provide electricity or power to specific uses and not the grid, such as for desalination to provide freshwater to communities, disaster preparedness and recovery, green hydrogen, aquaculture, ocean observation, marine transportation, marine carbon dioxide removal, and more (Cotter et al. 2021; LiVecchi et al. 2019; Thorson et al. 2022). Consequently, these non-grid uses will not affect local power consumption, especially relative to technologies like offshore or land-based wind (Freudenberg et al. 2023; Hevia-Koch & Klinge Jacobsen 2019; Komiyama & Fujii 2021; Traber et al. 2017) but may offer benefits to communities. Research about the environmental, economic, or social effects of MRE for some of these potential end-users exists (Li et al. 2018; Pérez-Vigueras et al. 2023), though this research is more limited. Further exploration into how these applications of MRE technologies may impact social and economic effects will be useful.

4.3. MEASURING SOCIAL AND ECONOMIC EFFECTS

Typically, social and economic effects are identified and documented through a baseline assessment during consenting processes as part of an environmental impact assessment (EIA), or other related assessment (e.g., social and economic impact assessment, social impact assessment, etc.) (Australian Government 2005; Dalton et al. 2015; Interorganizational Committee on Guidelines and Principles for Social Impact Assessment 1994; Karytsas et al. 2020; Mackenzie Valley Environmental Impact Review Board 2007; Ministère de l'Environnement, de l'Énergie et de la Mer, République Française 2017; Scottish Government 2022). Life cycle assessments (Lehmann et al. 2022, 2024; Soukissian et al. 2023) or risk assessments (Mehdi et al. 2020) can also be used. The type of assessment varies by jurisdiction and regulatory requirements (Freeman 2020). Information on requirements for social and economic data collection for each of the OES-Environmental countries is available online as supplementary material.

The magnitude of potential effects is predicted or modeled in these assessments and can be used to determine required mitigation or to select between alternative project designs or sites during consenting. The potential social and economic benefits are not usually included in these assessments, though are often used more informally to justify the rationale for pursuing a project (Karytsas et al. 2020). While such assessments are useful, once project execution has commenced, monitoring data is needed to confirm the predicted



effects and ensure just outcomes, including the distribution of costs and benefits of a new MRE project on a community (Interorganizational Committee on Guidelines and Principles for Social Impact Assessment 1994; Soukissian et al. 2023; Vanclay et al. 2015).

There remains a need to elucidate how social and economic data are collected and analyzed to measure effects from MRE and work toward standardizing approaches using the best available methods (Freeman et al. 2024). A review of the literature on social and economic data collection for MRE, as well as adjacent industries including other renewable energy and relevant marine sectors (e.g., offshore wind, fisheries, or tourism), found a wide range of methods and metrics for measuring effects (Freeman et al. 2024). The most commonly used methods included surveys, a variety of analyses (e.g., value chain; media content; strength, weakness, opportunity, threats (SWOT); etc.) and assessments (e.g., social life cycle, social impact, ecosystem services, etc.), case studies, models, and interviews. There was a large range of metrics used, but some often-reoccurring ones included acceptance, perceptions, employment and jobs, vulnerability, levelized cost of energy, and gross value added. Notably, metrics and methods were more established for economic data collection and assessment, while those focused on social aspects are still evolving and developing and diverged significantly. Additionally, the literature did not focus on assessing effects of MRE developments and was instead typically geared to methods or metrics for early stages of MRE development (planning, siting) or technology performance.

While improving measurements of social and economic effects is needed, developments have been made over time, including resources to aid such efforts. Several new tools have been created to address effects for MRE projects specifically, as described in Box 4.1.

BOX 4.1.
EXAMPLES OF TOOLS DEVELOPED FOR SOCIAL AND ECONOMIC EFFECTS OF MARINE RENEWABLE ENERGY (MRE)

Marine Energy Social and Economic Data Collection Toolkit (2024) – This toolkit was developed based on the recommendations from Freeman (2020). It aims to facilitate easy access to information on social and economic data for MRE and how to collect data and information for both baseline assessments and after project implementation, with examples. The toolkit also guides data collection efforts with a downloadable template for MRE developers to utilize.

Meaningful MRE Development Framework (2023) – This framework, described by Caballero et al. (2023), combines social lifecycle assessment, a social framework, and tenets of energy justice to generate a list of questions for conversations across design installation, operations and maintenance, and decommissioning for MRE.

Selkie Geographic Information System and Techno-economic Tool (2022) – Developed for MRE in Irish and Welsh waters, this open-source tool provides detailed spatial data that includes marine traffic, distance from ports, and fishing density to aid developers in siting wave or tidal devices as well as calculation of levelized cost of energy.

VAPEM (2022) – This tool, developed under the SafeWAVE project in Spain, is used to help manage marine activities, incorporate ecosystem services, and identify suitable wave energy development opportunities by including spatial assessments of environmental and human uses of ocean space.

Economic, Social, Spatial and Environmental (ESSE) Framework (2021) – This modeling framework can be used to assess impacts across multiple ocean-related industries, and has been applied for MRE by O'Donoghue et al. (2021).

Alaska Energy Data Gateway Community Metrics Explorer (2017) – This tool displays available data to evaluate the financial, human, and technical capacity of specific Alaska (United States) communities to undertake energy projects.

When collecting data for MRE projects, it is important to assure consistency, enabling the comparison of effects between projects and the identification of lessons learned and best practices. OES-Environmental has developed Good Management Practices (Copping et al. 2019) that have been updated to incorporate additional key considerations in collecting both baseline and monitoring data for social and economic effects (Table 4.1).

Table 4.1. Good Management Practices for collecting social and economic data for marine renewable energy (MRE). Original table from Copping et al. (2019) based on outcomes from two international workshops (Ocean Energy Systems & ORJIP Ocean Energy 2017, 2018), and recently updated based on feedback from Ocean Energy Systems (OES)-Environmental's Expert Forum on Social and Economic Effects in 2023.

Practice 1	Strategic-level data collection, analysis, and assessments should be carried out by the appropriate level of local, regional, or national government (or relevant agencies) to help understand benefits and effects of MRE projects. This data collection should take into account past experiences of communities with strategic-level efforts and be targeted to identify concerns that have been historically ignored. The use of jargon in soliciting information from communities should be limited.	
Practice 2	Specific questions should be developed that elucidate changes in social or economic conditions (either benefits or effects) for the communities and regions in which MRE development is planned. These questions should be co-produced or co-developed with communities to drive specific data collection efforts and analyses that reflect key needs and local values.	
Practice 3	Baseline social and economic data should be collected that address the current social and economic attributes, at the appropriate scale, prior to development.	
	Practice 3a: Baseline data for strategic assessments should be gathered by appropriate level of local, regional, or national government and applied to the most relevant geographic scale of the project area before development occurs.	**Practice 3b:** Project-level baseline data should be gathered by the project developer, assisted by existing supply chain companies and other local stakeholders as part of consenting processes before development occurs. If multiple projects are occurring on similar timescales, the project developers should be encouraged to collaborate to help gather data to inform strategic assessments.
Practice 4	Social and economic data should be collected once MRE development has occurred and the devices are operational. To the greatest extent possible, data should be collected using similar variables/methods as baseline data to allow for direct before/after comparison. This level of data collection may require extended project timelines or additional funding to ensure monitoring can be carried out.	
	Practice 4a: Social and economic data should be collected at the same scales, using the same methodologies for strategic-level assessments, by the appropriate level of local, regional, or national governments.	**Practice 4b:** Social and economic data should be collected at the same scales, using the same methodologies for project-level assessments, by the project developer, with assistance from supply chain personnel and other local stakeholders, including local governments.
Practice 5	Results from both social and economic assessments should be clearly communicated with communities involved in MRE developments, with a focus on transparency of methods, analyses, and purpose of the studies while avoiding jargon. Strategic-level assessment communication is the responsibility of the appropriate level of government, while project-level social and economic assessments should be jointly presented by the project developer and the appropriate level of government. Opportunities for participation and provision of feedback should be provided, including information on how feedback and input will be incorporated.	

4.4. EXAMPLES OF SOCIAL AND ECONOMIC EFFECTS FROM MRE

Though social and economic data collection specific to MRE is limited, there are examples from which to learn. Many of these have been highlighted throughout this chapter, and three case studies are described below to provide specific examples of social and/or economic effects of MRE. The documentation of experiential knowledge can enable other MRE projects to avoid pitfalls and improve project outcomes as they pertain to social and economic aspects.

STRATEGIC ECONOMIC EFFORTS AROUND MRE IN ORKNEY

Contributed by Jennifer Fox (Aquatera Ltd.) and Lisa MacKenzie (EMEC)

Location: Orkney, Scotland, United Kingdom (UK) (Figure 4.3), has long been at the forefront of MRE development due to its rich tidal currents and strong winds. The MRE industry has supplied sustainable energy and fueled economic growth in Orkney, generating jobs and attracting investment.

Approach: An independent economic audit was carried out in 2023 focused on the European Marine Energy Center (EMEC), one of the top 20 employers in Orkney, and the local and national effect of 20 years of operating the tidal and wave energy test site between 2003 and 2023 (EMEC 2023).

Key findings: The audit found that the creation of EMEC in Orkney and its activities have generated £370 million gross value added to the UK economy between 2003 and 2023. £130 million of that is estimated to have been accrued in Orkney. Additionally, £42 million has been invested in EMEC by public organizations such as Orkney Islands Council, Highlands and Islands Enterprise, and the Scottish and UK Governments. This indicates that for every £1 of public money invested, there has been an £8 return to the economy. Moreover, EMEC has secured £49.5 million of grant funding through competitively won projects, the vast majority of which were inward investments to the UK.

However, since 2020, the industry in Orkney has experienced a slowdown, with fewer devices being deployed and fewer developers investing in the region. Despite this, Orkney's necessity-driven innovation has propelled the region's supply chain to diversify and expand its businesses in many ways. In recent years, Orkney businesses have been exporting their expertise globally, particularly in areas such as capacity building, skills development, energy systems, battery storage, data storage, and hydrogen production. Companies based in Orkney like Leask Marine, Green Marine, Aquatera Ltd., and Orcades Marine have become world leaders in their fields, exporting their knowledge and services around the globe.

Lessons learned: The shift toward a holistic systems-based approach to renewable energy has been instrumental in driving Orkney's economic growth. There is progression from testing and demonstration of individual devices toward rationalization and commercialization, with a focus on systems and markets. This evolution has led to a stronger link between various energy components, including subsea batteries, wet-mate connectors, and energy storage systems.

Orkney's expertise in MRE has also facilitated its growth in the offshore wind industry, which is experiencing significant growth in Scotland. The transferable skills gained from MRE are invaluable, positioning Orkney's supply chain as a key player in this growing sector. Programs such as the Clean Maritime Demonstration Competition have further bolstered Orkney's reputation for innovation, with companies securing funding for hydrogen and e-fuel projects.

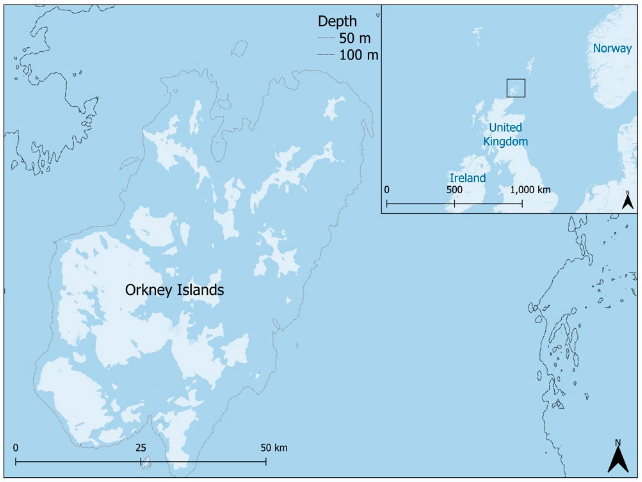


Figure 4.3. Orkney, Scotland, United Kingdom.

Excess renewable energy generated in the region prompted the exploration of alternative energy storage methods, with programs like ScotWind and Innovation and Targeted Oil & Gas considering establishing large-scale hydrogen production facilities in Orkney. The planned interconnector for the grid connection is poised to enhance Orkney's opportunities for growth, particularly in tidal energy projects and offshore wind. Additionally, the UK's recent subsidy program for tidal energy resulted in a number of tidal energy developers planning to demonstrate tidal energy arrays at EMEC.

Despite facing challenges, the region has leveraged its expertise and ingenuity to diversify its economy, export its knowledge globally, and embrace emerging opportunities in renewable energy. Through innovation and diversification, the region has solidified its place as a testbed and leader in sustainable energy solutions, both locally and globally.

PACWAVE SOUTH SITE SELECTION PROCESS AND SOCIOECONOMIC ASPECTS

Location: PacWave South (hereafter PacWave) is the first full-scale, grid-connected, pre-permitted wave energy test facility in the United States. It is located on the west coast offshore of Newport, Oregon (Figure 4.4). PacWave, which has been developed and will be operated by Oregon State University (OSU), is currently being constructed and plans to be operational by 2025. Newport is a hub of marine-based sectors including fishing and marine science/research, and OSU has a long history with wave energy including previously consented sites.

Approach: Site selection for PacWave involved an initial feasibility study, stakeholder engagement including with key sectors like the fishing industry, and community site selection teams that submitted proposals to OSU to determine the location of PacWave.

The feasibility study carried out in 2011 evaluated four potential locations off the coast of Oregon. The City of Newport where PacWave would ultimately be located, has good stakeholder representation and an existing relationship with Fishermen Involved in Natural Energy (FINE) as well as the necessary characteristics for the test site (proximity to ports and other required facilities, wave resource, water depth, soft bottom habitat, etc.) (Pacific Energy Ventures 2011). The feasibility study noted potential social and economic effects and how they may vary based on site selection. For example, effects on commercial fisheries would differ based on the chosen depth of the test site (e.g., the Dungeness crab fishery occurs in shallow depths and therefore would be impacted by a shallower site but not by a deeper site) and visual effects would be greater with a site located closer to shore or near marine headlands.

Two potential locations were then down selected, and Community Site Selection Teams were created to further assess developing the test site and to propose a location offshore (Oregon State University 2013). The Newport Community Site Selection Team included FINE and other key stakeholder representatives (Tribal, economic development, recreation, marine infrastructure, port, local government, utility, public) tasked with preparing and approving a site proposal for OSU's consideration. The Newport proposal included identification of existing infrastructure from other ocean uses (marine research, fishing, tourism, etc.) and avenues for developing space and/or facilities (e.g., cities or ports to assist, leases via city/county/state parks, using public space, cost-sharing options, etc.) to support PacWave. Human resources available were also noted including Newport's thriving working waterfront, workforce with applicable skills and knowledge from marine and supply chain industries (boat maintenance, marine research, technologically advanced fishing industry, etc.), and direct and indirect employment from marine-based businesses. The outcome of the Community Site Selection Team was a proposal that acknowledged these various components and an in-depth process to identify an offshore site that was approved unanimously and submitted to OSU in 2012. FINE specifically recommended a 6 nm^2 area based on technical criteria needed for the wave energy test site and fishing grounds; eventually a 2 nm^2 site was selected from this area and would become the PacWave test site (Freeman et al. 2022).

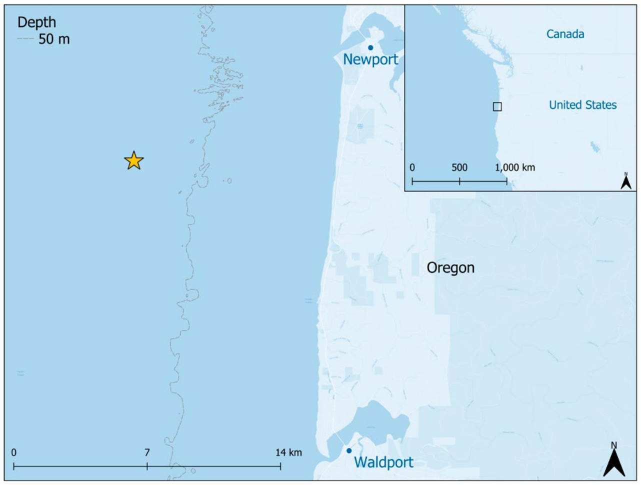


Figure 4.4. Location of the PacWave South wave energy test site in Oregon, United States (yellow star).

Lessons learned: Stakeholder engagement and the identification of social and economic components that may be affected, particularly impacts on the fishing community, were part of the PacWave consenting process. Bringing in stakeholders early, and in particular using a location proposed by FINE that reduced conflict, helped gain support for PacWave. An example of the support included a FINE representative who stated, "We're willing to give up good fishing assets because we're staunchly for natural energy research" (Oregon State University 2013). FINE also voted and recommended the offshore area which would become the PacWave site to the county Board of Commissioners citing decreased conflicts with fishing and other marine uses. It should be noted that while FINE, the Board of Commissioners, and the port were supportive of MRE development for research, there was strong opposition to further commercial-scale development that might use nearby areas of the Oregon coast and decrease viable fishing grounds (Oregon State University 2013).

SOCIOECONOMIC APPRAISAL OF THE NOVA INNOVATION SHETLAND TIDAL ARRAY: ENFAIT

Location: EnFAIT (Enabling Future Arrays in Tidal) was a European Union Horizon 2020 flagship project to advance tidal energy, led by Nova Innovation. The project included an assessment of the potential socioeconomic impacts of Nova Innovation's Sheltand Tidal Array, located in Bluemull Sound, Scotland, UK (Figure 4.5) (Norwood et al. 2023). The array initially comprised three 100 kW tidal stream turbines and was expanded to six turbines over the course of the project (see Chapter 6). The original three turbines were decommissioned in 2023, with the three remaining turbines expected to continue to operate in Bluemull Sound until at least 2038.

Approach: The initial socioeconomic appraisal was completed in 2018 and then revisited in 2023 and included an assessment of the positive and negative impacts of the Shetland Tidal Array on a range of factors. These included demographics, standard of living and housing, education, social cohesion, perception of energy resources, recreation and tourism, employment and business, industrial strategy and rural regeneration, commercial shipping and navigation, and regulatory framework. Effects were classified using a simple approach that included categories for 'clear and major positive effect', 'broadly supportive or minor positive effect', 'neutral effect', 'minor negative effect', 'major negative effect', and 'uncertain effect'. The appraisal was based on an initial review of published information on previous tidal energy projects and informed by extensive engagement with stakeholders including regulatory authorities, Shetland residents, local government representatives, and the Shetland Island Council. Residents on Yell, the closest inhabited island to the array, were specifically engaged through a mailed survey with questions on tidal energy and through an in-person event.

Key findings: Full details on the results of the socioeconomic appraisal are presented in the final report from the EnFAIT project by Norwood et al. (2023). Overall, no adverse effects were found. Positive effects were documented on employment and business through generation of additional knowledge, revenue, and capacity among the local companies used to produce key materials and services. In particular, the project demonstrated how the supply chain can rapidly adapt to emerging technologies that benefit local businesses through additional income and improved knowledge. It was found that further tidal developments could reverse the current trend of out-migration and preserve the existing demographic diversity. Notably, strong support for tidal energy was found among the local communities. It was noted that since Nova Innovation's tidal turbines are completely submerged, there are no visible structures which increased public support. The local community in Shetland also appreciated Nova Innovation's engagement with young people in schools which aimed to provide information about renewable energy and generate interest in marine science and engineering.

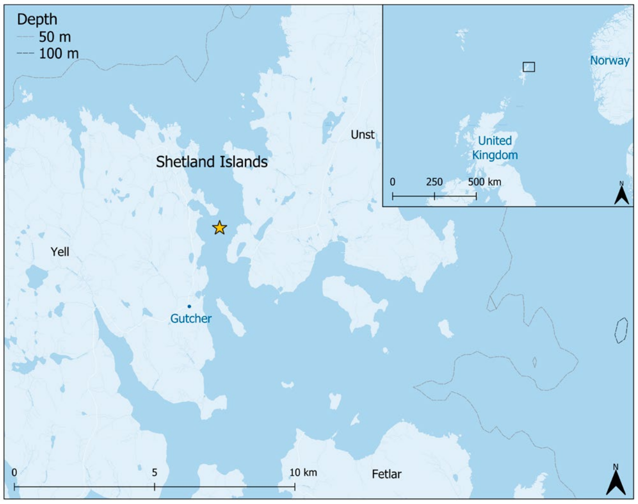


Figure 4.5. Location of the Nova Innovation Shetland Tidal Array in Scotland, United Kingdom (yellow star).

Lessons learned: Initially installing a small number of devices before scaling up was key to managing risk and limiting uncertainty from the perspective of the public and regulators. The initial installation of three devices demonstrated that there was no disruption to the existing users of the onshore or offshore area, including to other industries, providing reassurance and building awareness and support for tidal energy in the region. This was further demonstrated through additional activity including the expansion to six devices.

4.5. RECOMMENDATIONS AND CONCLUSION

This chapter provides an overview of the current research on social and economic effects, including those that have been experienced or are expected from MRE developments. Knowledge gaps remain based on the limited data to inform understanding of social and economic effects from MRE and, as such, lessons learned from offshore wind and other marine industries are drawn on. As the MRE industry progresses, it will become increasingly important to continue to study and understand MRE-specific effects at a strategic and project level, provide examples from MRE projects for the industry to learn and apply to future projects,

and develop guidelines on best practices for social and economic assessments. The Good Management Practices, updated for the *2024 State of the Science* report, offer some guidance for data collection. The recommendations from Freeman (2020) remain relevant and additional recommendations are detailed below.

4.5.1. STRATEGIC NEEDS

To improve understanding of MRE social and economic effects, there remains a role for government at all levels to play through strategic-level planning. Governments can provide policy changes or regulatory guidance that will lead to social and economic data collection and can financially support research and studies, as the industry is not in a position to take them on. These include:

- **Developing consistency in requirements and regulations for social and economic data collection and assessments.** Guidance and standardized approaches developed by the research community will facilitate this effort, along with the creation and support of regulatory communities of practice where nations can learn from each other and work toward best practices together. This may include development of new policies or regulatory guidance to create precedence to measure and consider social and economic dimensions of MRE where it does not already exist or to expand and enhance current policies or regulatory guidance so that data collection and assessments are comprehensive.
- **Conducting long-term assessments and monitoring, including at a regional scale.** As more activities and uses are added to the marine space, carrying out more in-depth assessments over longer timelines and at larger spatial scales will enable the identification of specific effects from MRE to be elucidated and compared to those from other industries and human activities. Governments also have a responsibility to gather industry-wide social and economic data that can help inform targeted assessments carried out by project developers for individual projects.
- **Increasing understanding of cumulative effects from activities and uses within the marine environment.** To fully understand the scope of human dimensions related to MRE, it will be important to understand the combined effects of other activities, uses, and development projects (see Chapter 9). This includes multiple MRE projects that occur within the same area and across industries such as offshore wind, fishing, and other marine sectors. Assessing and addressing cumulative effects necessitates coordination at a broader scale. Therefore, governments or other coordinating bodies are well suited to lead these strategic-level efforts.

4.5.2. RESEARCH NEEDS

Needs for additional research have been noted throughout this chapter, particularly knowledge gaps for social and economic effects of MRE and how different groups are affected. Researchers, governments, or other groups or organizations can increase the state of understanding by undertaking the following research needs and recommendations for data collection.

- **Using transdisciplinary methods for research.** Transdisciplinary approaches should focus on collaboration across a variety of fields, industries, regulatory bodies, and communities to find solutions to social, economic, and environmental issues. Doing so will allow for learning and co-production of knowledge, as well as challenges and needs to be addressed through diverse perspectives leading to more beneficial solutions (Steger et al. 2021).

- **Increasing understanding of indicators for MRE-specific effects.** Continued and expanded data collection will be crucial to highlight potential effects and to understand how various types and scales of MRE projects may affect communities, groups, and regions differently. For example, engaging with key companies and project developers can help gather basic data and metrics to both investigate effects of past and current MRE projects, and develop key indicators and variables for social and economic effects. As research is undertaken, data collection will need to address requirements based on the applicable regulatory context and responsibilities (see Figure 4.2). These actions will decrease the need to rely on adjacent industries to fill gaps and inform understanding.
- **Applying quality checks for data collection.** Data should be collected consistently throughout the MRE sector to enable comparison between projects, and to enhance conclusions and understanding of interactions and effects. More work is needed to identify how best to collect social and economic data consistently for MRE; the tools identified in Box 4.1 are a useful starting place. There is also a need for review, ideally by independent third parties, to assure the best available methods are used, carry out quality control, and reduce or avoid an undue burden on developers.
- **Creating standardized methods for data collection that can be applied internationally.** It is important to note that standardization of methods does not require development of international standards, as these are likely not practical for social and economic effects, which are too complex and variable and would miss the nuances required for each specific MRE project and community context. To achieve this, decision points can be characterized to advise which assessments are needed throughout MRE planning, development, and operation stages. Guidance can also be created to help identify what to consider, such as broad categories of data that will be important to include. Creating requirements for just and equitable outcomes could help, though ultimately data needs and outcomes for each project should be defined and co-developed with the relevant communities, groups, and stakeholders. As standardized methods are created, these will need to include common language, definitions, and other key factors that can help apply the methods internationally.

4.5.3. RESPONSIBILITY OF MRE INDUSTRY

Social and economic effects need to be understood and addressed for each MRE project to enhance benefits and avoid or mitigate negative impacts. This is largely the responsibility of the MRE industry, although information gleaned from government-funded strategic studies may be helpful.

- **Applying lessons learned from other industries.** MRE should learn from other industries such as the offshore wind sector, including what has not worked well and should be avoided. This will help fill current gaps in understanding. As research on MRE-specific social and economic effects increases, less reliance will be needed on analogous industries.
- **Improving approaches to address social and economic effects.** Developers have learned to be sensitive to environmental concerns and to plan accordingly, and the same approach is needed for social and economic aspects of MRE. The MRE-specific research and case studies presented in this chapter highlight some examples where this has already occurred in the MRE industry. Two important aspects include:
    - **Striving for just outcomes and equitable energy transitions.** Of particular importance is assessing the distribution of costs and benefits of an MRE project. Developing community benefits of MRE projects, particularly for communities or stakeholders that may be impacted, can also help achieve justice and equity in project development and even lead to communities feeling a sense of ownership or support for a project, which is important in an emerging industry like MRE.
    - **Understanding and incorporating diverse perspectives among and within different groups.** The range of effects that stakeholders experience should be evaluated throughout MRE planning, development, and operation to maximize benefits and minimize negative impacts. This will help work toward meaningful engagement with communities and groups around an MRE project.

- **Bringing together marine activities to address social and economic effects.** To achieve sustainable development within the blue economy, MRE developers can look toward comprehensive marine spatial planning and co-location of activities (see Chapter 6). Working with communities and regions to understand existing uses and where MRE can supply power or share space and resources can help maximize benefits from MRE and lessen impacts on current uses. This will likely require some government support, particularly for pilot or demonstration co-location projects, as well as industry collaboration between MRE and other maritime industries.

Even though there are limited data and information on social and economic effects from MRE projects and associated research, there are lessons from other industries that can help in the meantime, and research from MRE projects has been increasing over the years. Making progress on the above recommendations and filling knowledge gaps on MRE-specific effects, particularly regarding the various groups identified in this chapter, will advance our understanding of how MRE can affect social and economic aspects and human dimensions. To achieve greater understanding, the broader MRE community will need to come together, share learning, and work toward standardization of approaches.

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Suggested citation:

Freeman, M. C., and Rose, D. J. 2024. Social and Economic Effects of Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 104-142). doi:10.2172/2438591


LIVE SMART
STADIUM
WORK HARD 100%
20k
FLIGHT 5%
positive vibes!
TRY!
Don't give up!
courage

5.0

Stakeholder Engagement for Marine Renewable Energy

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Stakeholder engagement is a critical piece of any new development project that affects public or private interests. Effective, thoughtful engagement and participatory activities early in the planning process of a project can help planners and project developers understand local concerns, adjust designs to avoid negative environmental impacts, select the best site for a project, answer questions, reduce delay, enhance opportunities and benefits, and build support for a project (Cuppen et al. 2016; Portman 2009; Wiersma & Devine-Wright 2014). On the other hand, cursory or inadequate engagement that is viewed as "checking the box" or tokenism is unlikely to be effective, and can result in project failures, diminished trust, strong opposition, or costly, drawn-out processes (Butcher & MacLennan 2020; Garard & Kowarsch 2017; Gill & Rand 2022; Jolivet & Heiskanen 2010; Pizzi et al. 2021; Sterling et al. 2017).

Marine renewable energy (MRE) projects are no different. Stakeholder concerns can drive decisions around siting, environmental monitoring, and what happens with the energy generated (Dvarioniene et al. 2015; Han et al. 2024; Heuninckx et al. 2022; Standal et al. 2023). Stakeholders may also initiate projects with developers or fill the role of a community advocate for MRE to get projects implemented (e.g., Ruggiero et al. 2014; Simpson 2018), especially in the early phases of the industry. Freeman (2020) briefly explored stakeholder engagement for MRE, highlighting several factors that make for successful engagement for MRE. These include having a well-designed, participatory approach starting early on in or prior to the planning phase, that incorporates partnerships; understanding community context and the legacy of past developments (both MRE and from other industries); transparent communication with two-way learning and information exchange; and building trust (Delvaux et al. 2013; Kerr et al. 2015; Simas et al. 2015; Wahlund & Palm 2022; Yates & Bradshaw 2018).

Several guides exist to aid project developers in conducting stakeholder engagement for MRE (Baulaz et al. 2023; Delvaux et al. 2013; ETIP Ocean 2023; Isaacman & Colton 2013; Seafood/ORE Working Group 2023), as well as many from other industries such as energy planning (Natural Resources Canada 2014; REScoop.eu 2021; Ross & Day 2022; Skill et al. 2020), resource management (Betley et al. 2018; Brill et al. 2022; Haddaway et al. 2017; Poetz et al. 2016; Slater et al. 2020), and more. While there are vast resources and guides for stakeholder engagement, the goal of this chapter is to summarize the recent literature around MRE, identify approaches used for MRE developments, and amplify the lessons learned from past MRE projects. Based on the literature and examples, the chapter offers recommendations for improving MRE stakeholder engagement that can result in better experiences and outcomes for local communities and for MRE.

5.1. STAKEHOLDER ENGAGEMENT ACROSS INDUSTRIES

The goal of stakeholder engagement is to provide opportunities for participatory decision-making, community empowerment, and co-design where appropriate. Building on the ladder of public participation developed by Arnstein (1969) as well as the spectrum of public participation (Figure 5.1) (IAP2 2018), opportunities for public participation occur along a spectrum from one-way information transfer designed to inform or educate to two-way dialogue and collaborative partnerships (e.g., involve, collaborate, empower). A ladder of participation specific to marine spatial planning has also been developed by Morf et al. (2019). In all cases, moving up the ladder or along the spectrum represents an increase in participation in decision-making processes and a resulting increase in stakeholder influence on outcomes (Coy et al. 2021).

In contrast to outreach and education (see Chapter 7), stakeholder engagement goes beyond telling the public what they should know ('Inform') and moves toward two-way communication that includes opportunities for input ('Consult' and beyond). Education and raising awareness are often key components of engagement efforts such as community meetings but are not the only goals and should not come at the expense of listening to the community. The assumption that providing scientific or project information alone will drive acceptance of MRE or other renewable energy projects is based on the knowledge-deficit model (lack of scientific understanding alone, leads to lack of public support), a concept that has been refuted in many contexts, mainly due to its oversimplification of often complex issues (Brunk 2006; Cook & Melo Zurita 2019; Grant 2023; Seethaler et al. 2019; Simis et al. 2016; Sturgis & Allum 2004; Suldovsky 2017). However, familiarity with MRE remains low as MRE is an up-and-coming industry, which will factor into how stakeholders and community members are engaged—needing to start from a place of learning about technologies, potential effects, and uncertainties, and addressing misconceptions or misunderstandings (Dalton et al. 2015; Stokes et al. 2014). While the MRE industry is not yet mature and there

INCREASING IMPACT ON THE DECISION

PUBLIC PARTICIPATION GOAL

INFORM	CONSULT	INVOLVE	COLLABORATE	EMPOWER
To provide the public with balanced and objective information to assist them in understanding the problems, alternatives, opportunities and/or solutions.	To obtain public feedback on analysis, alternatives, and/or decisions.	To work directly with the public throughout the process to ensure that the public concerns and aspirations are consistently understood and considered.	To partner with the public in each aspect of the decision including the development of alternatives and identification of the preferred solution.	To place final decision making in the hands of the public.

Figure 5.1. International Association of Public Participation (IAP2) Spectrum of Public Participation. Adapted from IAP2 (2018).

is limited documentation of stakeholder engagement processes, as it continues to grow, it will be important to share more information related to steps higher on the spectrum of public participation.

Lastly, stakeholder engagement is a critical piece of just energy transitions and is of particular importance in the unique coastal regions where MRE is likely to be developed (Bennett 2022; Caballero et al. 2023). Discussions of equity and energy justice in project planning emphasize the need to identify barriers to justice throughout planning, development, and implementation (Cisneros-Montemayor et al. 2022; Jenkins et al. 2018; Sankaran et al. 2022; Withouck et al. 2023) and include aspects of recognition justice, procedural justice, and distributional justice (see Chapter 4). As an emerging industry, MRE has the opportunity to intentionally advance social justice and avoid or repair (via restorative justice) some of the pitfalls of previous energy transition or infrastructure projects (Cisneros-Montemayor et al. 2022; Desvallées & Arnauld de Sartre 2023; Duff et al. 2020; Dutta et al. 2023; Fouquet 2010; Hoffman et al. 2021; Kouloumpis & Yan 2021; Lockwood et al. 2017; Sankaran et al. 2022; Skjølsvold et al. 2024; Watts 2018).

5.2. APPROACHES TO STAKEHOLDER ENGAGEMENT FOR MRE

Legal and regulatory frameworks have been identified as playing a key role in establishing requirements for engaging local stakeholders in the decision-making process around specific projects (Lange et al. 2018; Salvador & Ribeiro 2023; Sorman et al. 2020). Examples of requirements related to engagement activities in several OES-Environmental countries are described in supplementary material. These frameworks vary by jurisdiction and can include formal or informal requirements for public participation in development processes or impact assessments (Dunphy et al. 2021), development and distribution of community benefits (Cisneros-Montemayor et al. 2022), or consideration of environmental and energy justice (Paslawski 2023; United Nations Economic Commission for Europe 2014). Many countries do not yet have clear guidance for comprehensive stakeholder engagement related to MRE projects due to the status of the industry (Delvaux et al. 2013; Freeman 2020; Simas et al. 2015). The variability of national policies in different countries and the lack of uniformity in procedures is considered as one of the main non-technological difficulties of MRE development (Apolonia et al. 2021).

Most projects are required to carry out some level of public consultation (Vasconcelos et al. 2022), and in many cases, engagement activities hosted by project developers go beyond what is legally required for consultation (Baulaz et al. 2023). These types of early, continued, and authentic engagement are the most successful across renewable energy development projects (Salvador & Ribeiro 2023). Several resources, guides, and publications offer suggestions for MRE and how best to engage with stakeholders around developments to increase project success and achieve social license (Baulaz et al. 2023; Delvaux et al. 2013; ETIP Ocean 2023; Isaacman & Colton 2013; Kelly et al. 2017; Norwood et al. 2023; Seafood/ORE Working Group 2023).

Key aspects of stakeholder engagement include identifying who is responsible and will carry out engagement and outreach, who the stakeholders are, and what approaches will best fit a project and the associated community or stakeholder group. In most cases, the project proponent or developer will be responsible for engagement as the lead for development. There are some instances, particularly when required by law, where a government agency or entity considered to be neutral and independent, may be responsible for engagement with stakeholders. In other cases, it may be a third-party group that a project proponent has brought in to carry out the engagement or who fills the role of a trusted third party to help objectively facilitate engagement and negotiations (Bessette et al. 2024; Jami & Walsh 2017). There may also be instances where a community has initiated engagement—considered a bottom-up approach—which changes the responsibility. In any of these scenarios, it is important to clearly define who is responsible for each aspect of stakeholder engagement.

Identifying the stakeholders for a particular project is key to any engagement and outreach effort. In general terms, stakeholders have been defined as anyone who has an interest in the MRE development and who can either affect or be affected by the development itself or associated actions, objectives, and policies (Isaacman & Colton 2013). It can be incredibly difficult for MRE projects to define who exactly the stakeholders or affected communities may be, due to the wide range of potential environmental, spatial, social, and economic effects. The public should also be included in engagement, though they may not be directly affected. Stakeholders may change throughout the different stages of a project or may differ by MRE technology or project location (Johnson et al. 2015), and may include government agencies, supply chain businesses, employees, unions, local residents, business owners and operators, fishers, tourism operators, non-governmental organizations, community groups, and more.

Indigenous groups are important to include for engagement, but they are not merely stakeholders and this should be acknowledged through meaningful, appropriate engagement, for instance as partners, beneficiaries, and/or stewards (Hunter et al. 2023; Kerr et al. 2015; Lyons et al. 2023) (see Chapter 4). While some Indigenous groups have statutory rights and formal consultation in many countries, these have been noted as inadequate, ineffective, or generally lacking in practice (Adeyeye et al. 2019; Bacchiocchi et al. 2022; Hedge et al. 2020; Maxwell et al. 2020; Parsons et al. 2021). Working with Indigenous groups requires relationship building; respecting cultures, traditions, and histories; being adaptable and flexible; and ideally, inclusion by way of full participation and consent (Hunter et al. 2023; Richardson et al. 2022). Indigenous knowledge and perspectives are unique and important, and Indigenous peoples should be involved throughout decision-making processes, including project design and siting, consenting, and benefits agreements (Duff et al. 2020; Richardson 2021). Hunter et al. (2023) provide a cultural license to operate a framework that centers industry partnering with Indigenous groups and maximizing co-benefits, and which can be applied to blue economy sectors like MRE. MRE project developers must explore how each Indigenous group wants to participate and be engaged.

Throughout engagement efforts, it is imperative to have diversity in representation from stakeholder groups and that meetings, forums, and resources are accessible in a variety of ways (Dunphy et al. 2021; Isaacman & Colton 2013). This also means assuring that the loudest voices in a community are not the only ones heard, and that hard-to-reach or typically marginalized groups are included. For stakeholders who do not choose to engage, information can be made readily available through a variety of formats (e.g., local newspapers, bulletins, resources at local businesses) to allow for anyone to remain informed or engage at a later date. A few examples of successful approaches for identifying stakeholders that have been used or recommended for MRE include community profiles (Dunphy et al. 2021), a stakeholder salience framework (Johnson et al. 2015; Mitchell et al. 1997), and comprehensive stakeholder mapping (Baulaz et al. 2023; Bennett 2022). Beginning with key informants, community leaders, or project champions can help to define the breadth of stakeholders surrounding a development. In addition

to defining stakeholders, it is important to acknowledge how each group may affect or be affected by an MRE development (see Chapter 4), how they want to be engaged, and their desired level of participation (Baulaz 2023; Johnson et al. 2015). The identification of stakeholders may also elucidate intermediate or representative actors who are trusted by and part of the community to relay information about the MRE project or represent stakeholder groups as part of a project steering or advisory committee (Baulaz et al. 2023). Specifying stakeholders and target audiences at the beginning of project conception and reevaluating throughout the life of a project is necessary for any successful engagement effort (Johnson et al. 2015).

Determining the engagement formats and sequencing approaches that work best for a particular project, location, or stakeholder group is another important aspect of planning stakeholder engagement for MRE (Baulaz et al. 2023; Bennett 2022). While there are numerous approaches and methods, a few examples from MRE are provided here. Dunphy et al. (2021) recommend moving toward a "consult-consider-modify" model rather than making decisions ahead of time and informing stakeholders too late in the process, and allowing the motivations for engagement to define method and scope. Delvaux et al. (2013) recommend the use of participatory approaches to engagement to increase accessibility of the process. Isaacman and Colton (2013) provide a guide for community engagement for tidal energy in Nova Scotia, Canada, that details a step-by-step approach to develop and implement an engagement plan.

Sharing specific examples of community engagement plans from past and current MRE developments can be useful for MRE developers and project proponents to learn from one another. For example, BioPower Systems (2015) created a community consultation plan for their Port Fairy, Australia, pilot wave energy project that follows the inform, consult, and involve steps of public participation (Figure 5.1). The plan lays out the stakeholders affected and their desires, attitudes, and values; associated risks from the project and responses; and clearly states how BioPower Systems will communicate with and notify the community, and how the community can provide feedback. The EnFAIT project provides another example of documenting specific stakeholder engagement efforts from Nova Innovation's Shetland Tidal Array in the United Kingdom, with the intent to benefit other tidal energy projects (Norwood et al. 2023). Under this project, a local community engagement strategy was implemented that followed the inform, consult, and involve steps of public participation, including engaging with the community through a mail survey, participation at a local fair, and several rounds of focus group discussions with the public and in local schools with youth. They also had a goal to evaluate the effectiveness of these local engagements so that lessons learned could be shared with other developers. Because MRE is a developing industry with frequent changes to technologies and consenting processes, it will be necessary to continue to evaluate these shared approaches and strategies for effectiveness (Johnson et al. 2015).

5.3. GOALS OF STAKEHOLDER ENGAGEMENT FOR MRE

Key to stakeholder engagement for MRE is gaining input and reflecting the values of stakeholders and communities to understand if a project is suitable for a particular location from a technical, social, economic, environmental, and regulatory perspective. Then, and only if appropriate, the project can be developed considering the specific context of that location to assure community support, beneficial social and economic outcomes, and reduced socioeconomic and environmental impacts. Several goals or functions of stakeholder engagement have been identified through a review of the recent literature for MRE.

Sharing information between a developer or project proponent and the community is a typical early goal of stakeholder engagement. From the developer, this could be in the form of education or sharing informational materials about the project or technology to increase public awareness, though strategies for information sharing may vary with local contexts due to preferences, existing mechanisms for engagement within a community, and technology (e.g., computers, internet) availability (DeSanti 2020; Isaacman & Colton 2013; Kallis et al. 2021; Ramachandran et al. 2020, 2021). The community may share information that includes: potential environmental or socioeconomic effects, spatial or temporal data and information about potential project sites (Reilly et al. 2016), local and traditional knowledge (Dunphy et al. 2021; Molnár et al. 2023; Noble et al. 2020), suggestions for deployment methods (Baker 2021), feedback on the proposed project (Slater et al. 2020), and local supply chain and workforce capacity and opportunities (Norwood et al. 2023). Information can also be provided and collected by third parties, through strategic government efforts (Department of Fisheries and Oceans Canada 2022; RPS Group 2010; Welsh Government 2022b, 2022a) or research (Garrett et al. 2022; Gunn et al. 2022). A key aspect of information sharing is that it should be started as soon as possible, ideally before any critical project decisions are made (Delvaux et al. 2013; Gopnik et al. 2012; Isaacman & Colton 2013).

Understanding the unique opportunities or barriers for MRE within a specific context, including stakeholder values, perceptions, and key social, economic, environmental, or cultural features is another goal of stakeholder engagement (Axon 2022; Boudet et al. 2020; Choi et al. 2022; de Groot & Bailey 2016; DeSanti 2020; Elrick-Barr et al. 2022; Hooper et al. 2020; Howell 2019; McMaster et al. 2024; Theodora & Piperis 2022). Establishing effective venues and formats for engagement with a community allows for opportunities for two-way communication, which can enable understanding of local values and context as well as barriers and opportunities for MRE development. This could be through direct solicitation of values or priorities in a structured engagement process, research study, or framework (Bonnevie et al. 2023; Custodio et al. 2022; de Groot & Bailey 2016; Devine-Wright & Wiersma 2020; Dreyer et al. 2019; Kazimierczuk et al. 2023; Richardson et al. 2022; Trifonova et al. 2022), or informal avenues like community dinners, open houses, or social media (Leal Filho et al. 2022; Melnyk et al. 2023). Meeting people where they are by aligning engagement activities to familiar community formats and ongoing community-based efforts (e.g., existing organizations) acknowledges community structures and allows for more fruitful discussions to address barriers and strengthen opportunities throughout the planning process (Apolonia et al. 2021; Borges Posterari & Waseda 2022; Friedrich et al. 2020; Howell 2019; Kallis et al. 2021; O'Hagan et al. 2016).

In addition to gaining information about community values, stakeholder engagement can aid in the design and siting of MRE projects to select the most appropriate technologies and locations. This includes collecting spatial information from current users of the marine environment (e.g., fisheries, tourism, navigation, etc.) and regulatory stakeholders for identifying co-use opportunities, conflict, culturally important areas, optimal locations (with grid connection, if applicable), energy end-uses, and deployment and maintenance considerations (Bakker et al. 2019; Dvarioniene et al. 2015; Kallis et al. 2021; Maisondieu et al. 2014; Pollard et al. 2014; Reilly et al. 2016; Xavier et al. 2022). Some of these activities may have already been conducted as part of marine spatial planning processes to designate larger regions for energy use (Janssen et al. 2015; Quero García et al. 2019, 2020; San Filippo 2013; Yates & Bradshaw 2018). However, some additional stakeholder engagement will likely be required before selecting an MRE site, even if the project is developed within areas designated for MRE (Alexander et al. 2012; Johnson et al. 2016; Pisacane et al. 2018; Quero García et al. 2021). Considering stakeholder preference on project visual design elements (surface expression, shape, paint color, markers, or associated land-based infrastructure) as well as input on operational design (seasonality of deployment or operation, maintenance needs, plans to scale up, grid interconnection) and business strategy (local partnerships for labor, supply chain, or distribution infrastructure) in the early phases of project planning can save developers time and money by not investing in technical decisions that may not be considered acceptable (Bucher et al. 2016; Cavagnaro et al. 2020; Freeman et al. 2022; Haslett et al. 2018; Jenkins et al. 2018; Kujanpaa 2020; Peplinski et al. 2021). Flexibility on the part of the MRE developer and the community is more likely to result in a successful project; this includes incorporating community input on design and siting in project planning and decision-making when possible, as well as understanding technical or resource limitations that may require compromise (Gram-Hanssen 2019; Li et al. 2022).

Another primary goal of stakeholder engagement is to build trust between the developer and stakeholders. In many locations, some level of stakeholder support or social license is required as part of obtaining consent for a project. Renewable energy projects—regardless of the technology—in which a community has a high level of trust in the developer to comply with regulatory requirements, to provide accurate and timely communication, and to execute on promised benefits are much more likely to be successful (Delvaux et al. 2013; Dwyer & Bidwell 2019; Firestone et al. 2020; Heras-Saizarbitoria et al. 2013; Kallis et al. 2021; Lange et al. 2018; Liu et al. 2019; Segreto et al. 2020). On the other hand, projects where the developer is considered untrustworthy and lacks community support more often face significant barriers and opposition, including protests or legal actions, and are unlikely to move forward regardless of their purported benefits or economic/technical feasibility (Comeau et al. 2022; Fleming et al. 2022; Grosse & Mark 2023; Jørgensen 2020; Park et al. 2022). Social license is not always stable or constant and can be lost at any time during project planning, development, or implementation, so developers need to plan for transparency and consistency, as well as build and maintain long-term relationships (Kelly et al. 2017; LaPatin et al. 2023; Lyons et al. 2023; Uffman-Kirsch et al. 2020).

Lastly, stakeholder engagement activities are a key way to identify and plan for benefits with community members as well as define potential negative impacts and associated mitigation needed for project activities. This can be formalized in a community benefits agreement as an output, or more informally agreed upon between stakeholders and the developer (Glasson 2017; Kerr et al. 2017; Rudolph et al. 2018). Emphasizing benefits in community discussions has been recommended to maximize the potential for MRE adoption, as opposed to only focusing on negative impacts (Howell 2019). There are numerous ways to develop and equitably distribute financial and nonfinancial benefits from MRE, such as exploring ownership models, feed-in tariffs to support community-scale investments, data sharing, coastal protection, and community development funds for additional projects (Cisneros-Montemayor et al. 2022; Isaacman & Colton 2013; Kularathna et al. 2019; Regen 2022; Suda et al. 2021; Tarr & Lionais 2012). Preferences for benefits or mitigation will vary by community context, and weaving these discussions into stakeholder engagement activities enables the identification of appropriate options or the generation of novel solutions to fit the place and project (Kallis et al. 2021; Tyler et al. 2022).

5.4. EXAMPLES AND LESSONS LEARNED FOR MRE

There are many examples from MRE and other industries to draw upon for successful stakeholder engagement. Sharing lessons learned is becoming a key practice in the MRE industry as well as for other coastal development sectors. As the industry evolves, there will be less need to rely on learning from other industries, such as offshore wind, in planning MRE projects—though it will still be important to consider the context of particular places and the various projects that are being discussed in shared marine spaces in order to successfully navigate stakeholder conversations.

Several case studies for MRE are described by Dunphy et al. (2021) and Delvaux et al. (2013). Dunphy et al. (2021) offer insights from stakeholder engagement at MRE projects in Europe including Wave Hub (England), Mutriku (Spain), Pentland Firth and Orkney Waters Pilot (Scotland), Biscay Marine Energy Platform (BiMEP, Spain), SEM-REV Test Site (France), and Aguçadoura Test Site (Portugal). Delvaux et al. (2013) also provide information from several MRE projects or potential areas for development in Europe, including at Paimpol-Bréhat (France), Bay of Saint Brieuc (France), Fromveur-Ouessant (France), and the European Marine Energy Centre (Scotland). The examples below illustrate stakeholder engagement activities from around the world that demonstrate lessons learned for MRE.

ENGAGEMENT ACTIVITIES AROUND THE EFFECTIVE LIFETIME EXTENSION IN THE MARINE ENVIRONMENT FOR TIDAL ENERGY (ELEMENT) PROJECT

Project description and location: The ELEMENT project was developed from 2020 to 2023 with funding from the European Union to bring together tidal energy partners for community engagement activities in Brittany, France. Partners included Nova Innovation, IDETA, ORE Catapult, Chantier Bretagne Sud, Guinard Énergies Nouvelles, France Énergies Marines, and InnoSea (hereafter ELEMENT team). The ELEMENT team identified stakeholders within four communities – Belz, Etel, Plouhinec, and Sainte-Hélène – near the tidal test site in the Etel estuary (Figure 5.2).

Approach: The ELEMENT team participated in three stakeholder engagement events before the tidal turbine was placed in the water for testing. All information and materials were made available in French to be widely accessible to the community.

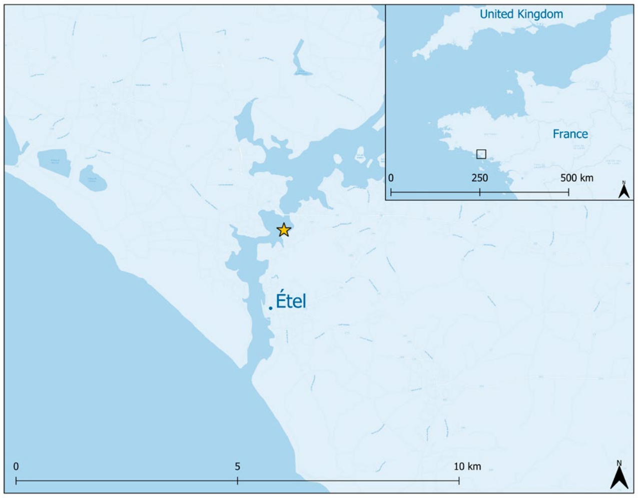

Figure 5.2. Location of the ELEMENT tidal energy deployment in the Etel estuary in France (yellow star).

1. In June 2022, the Nautical Commission (consultative commission of local community marine users) met with members of the ELEMENT team to discuss the project, view the test site, and share their observations and recommendations.
2. In October 2022, the ELEMENT team presented the project information to the local community at Belz Town Hall and feedback was requested via survey.
3. In February 2023, the ELEMENT team organized a site visit to display the Nova Innovation RE50 tidal turbine before deployment. The site visit was attended by local authorities, interest groups, businesses, and the press.

Key findings: Participants at each event showed interest in the project and wanted to understand the tidal technology. These events resulted in:

1. The Nautical Commission considering the risk to recreational fishing and pleasure boating for the project as low, and therefore did not need to be restricted. Overall, the Nautical Commission was in favor of the tidal turbine deployment (Lehnertz 2023).
2. Findings from the town hall meeting with 75 attendees and 15 surveys completed; 100% of surveys were in favor of tidal technology and 87% of respondents believed that the ecological footprint of an electricity source is the most important aspect to understand (Lehnertz 2023).

3. The site visit, which was attended by 17 participants, being covered by the press through a variety of news articles (Lehnertz 2023).

The four local communities near the Etel estuary showed strong support for the ELEMENT project and did not trigger any opposition.

Lessons learned: Relaying information from the Nautical Commission to stakeholders in the area was important for understanding the potential impacts of the project on recreational uses. The successful outcomes and support achieved for the project were due to communication early in the development process and hosting multiple community outreach events with a variety of stakeholder groups tailored to the local area of interest (Lehnertz 2023).

RESEARCH ON COASTAL COMMUNITY PERCEPTIONS IN THE CHANNEL ISLANDS (ALDERNEY)

Contributed by Emily Wordley (Huddersfield University)

Project description and location: The France-Alderney-Britain (FAB) Link is a proposed electricity interconnector cable between France and the United Kingdom, originally planned via Alderney (Figure 5.3). While it would not directly deliver electricity to Alderney, a project objective was to provide a potential export route to market for the future development of tidal energy in Alderney's territorial waters. This option would have included a cable route and converter station located in Alderney. Significant local opposition occurred, including anti-FAB protests and anti-FAB propaganda during the height of project discussions in 2016 and 2017. In July 2022, the project announced that it would not make landfall in Alderney and would pursue another route around the island.

Approach: A research study was conducted, using qualitative research methodologies to explore individual experiences and perceptions toward the FAB project and to understand the role of trust and perceived fairness within the planning process. This data collection was not required as part of any regulatory or licensing process but was undertaken for academic purposes. Semi-structured interviews were undertaken with Alderney residents, government, and industry-development representatives during site visits in May and October 2022. The research included elements of ethnography and observation, with the researchers engaging in informal conversations with local business owners and attending community events and government-led public engagement events. It is important to note that this approach to data collection was guided by the principles of a constructivist framework (where researchers are active participants and as such construct their understanding based on their own experiences) with an emphasis on understanding the meaning behind individual experiences and perceptions of fairness and trust. Therefore, knowledge gleaned is a subjective interpretation of participant descriptions and explanations of experiences and perceptions.

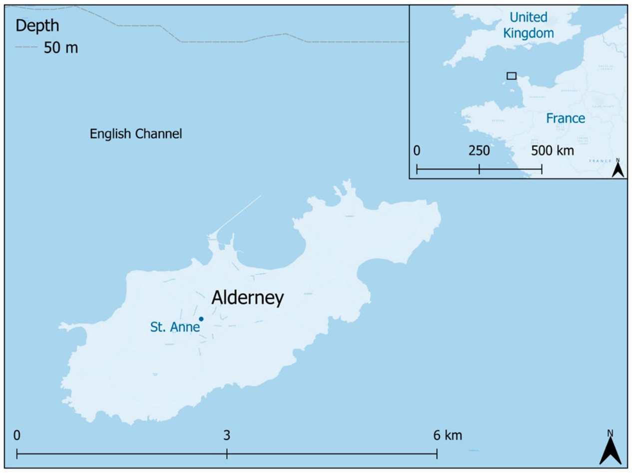

Figure 5.3. Alderney located in the English Channel between the United Kingdom and France.

Key findings: The social impact of FAB was evident through resistant behaviors, including community protests, formation of an opposition group, and ongoing intra-community conflict. Low levels of community trust were observed toward FAB Link project objectives and project decision-makers, attributed to a perceived lack of transparency and community power within the planning process (procedural justice), alongside perceived unfairness in the distribution of benefits (distributive justice). There was also local skepticism toward the motives and authenticity of individuals leading the community engagement due to a lack of knowledge and understanding of local impacts, combined with the timing of engagement, which occurred after critical project decisions were already made by the local government.

Lessons learned: Local experience with the FAB project eroded trust toward project decision-makers, including external and local industry developers, as well as the local government. This loss of trust threatens the successful implementation of future renewable energy projects and policies. Failure to rebuild and maintain trust may lead to further local resistance to energy development projects, resulting in additional costs and delays to achieving island decarbonization. Rebuilding trust starts with early, transparent meaningful engagement, sustained from planning to decommissioning of a project (Cvitanovic et al. 2021). Any engagement must be a two-way partnership process, assuring community power within the decision-making process.

MARINE SPATIAL PLANNING SUPPORTING MRE DEVELOPMENT IN BRITISH COLUMBIA, CANADA

Project description and location: The Marine Plan Partnership for the North Pacific Coast (MaPP) is a marine spatial planning initiative developed in partnership with the Province of British Columbia of Canada with 18 member First Nations to implement marine use plans. These plans encompassed four sub-regions: Haida Gwaii, North Coast, Central Coast, and North Vancouver Island (Figure 5.4). Advisory committees for each sub-region representing marine stakeholders from multiple sectors were formed, beginning in 2011 and meeting approximately every two months through 2014. Public input was solicited in spring 2014 and the final plans were released in 2015. It should be noted that none of the plans are legislated or legally binding at this time.

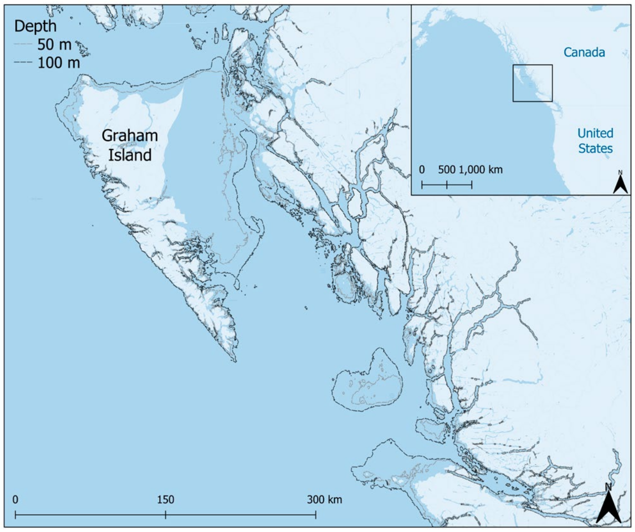

Figure 5.4. Location of the Marine Plan Partnership for the North Pacific Coast marine spatial planning initiative in British Columbia, Canada.

Approach: The approach to stakeholder engagement utilized in the MaPP was based on five principles clarified in a letter of intent to collaborate that was agreed to by all partners: openness, transparency, inclusiveness, responsiveness, and informed input. The signed letter of intent also outlined engagement tools such as advisory committees, open houses, bilateral sessions, and a website to support the planning process. The advisory committee included the province, partner First Nations, and other stakeholders representing a wide range of sectors and interests. Spatial plans were co-developed by First Nations and the provincial government as Indigenous knowledge and co-governance were integral to the plan (Diggon et al. 2021). Following this, stakeholder and public engagement activities were carried out to achieve broad engagement throughout the planning process (McGee et al. 2022).

Key findings and lessons learned: The MaPP is considered a successful example of a collaborative planning process that balances economic development with the protection of ecological and cultural values. A key factor in this success was that the process was preceded by First Nations territorial marine planning, allowing First Nations' priorities to drive further planning as a "step zero" in marine spatial planning, before the public engagement began (Diggon et al. 2021). First Nations were able to build capacity within communities, compile robust spatial datasets while protecting sensitive information, link specific goals to implementation structures at the regional scale, and secure and protect key values and areas within their territories from external stressors (Diggon et al. 2021). In addition, extensive early and sustained engagement with MaPP partners led to success, with high levels of stakeholder influence and input on the final plans. Factors contributing to this effective engagement approach, as described by McGee et al. (2022), include:

- Sufficient funding for engagement activities with advisory committee members,
- Inclusive representation of stakeholders and ocean user groups,
- Accountability of leaders that built trust in the planning process,
- Providing clear definitions of terms across plans,
- Third-party consultants that provided unbiased meeting and stakeholder support,
- Opportunities to build relationships, and
- Commitment to engaged stakeholders to maintain the advisory process throughout the planning activities to implementation.

MaPP project team members regularly share their experience and lessons learned at workshops and conferences internationally to support others in collaborative marine planning efforts.

Application to MRE: Richardson et al. (2022) conducted a study that built on the established marine spatial planning within MaPP to investigate the practical tidal energy resource that could be extracted in the region. Their holistic framework used the previously determined marine plans, coupled with local values and acceptability of tidal energy, to identify potentially suitable locations for tidal energy development. They suggested that identified sites could be used to update and further refine Special Management Zones within the MaPP regional plans for tidal energy. This approach to siting for MRE enabled the identification of low-conflict areas based on previously collected spatial data and stakeholder engagement processes to aid siting, reduce concerns over particular projects, and streamline the remaining engagement needed at the project level.

5.5. RECOMMENDATIONS AND CONCLUSION

Stakeholder engagement is a key piece of any development project. With MRE still in early stages, it is especially important to carry out responsible, comprehensive, and equitable engagement to aid project development and to move toward positive public perceptions of the industry.

5.5.1. ENGAGEMENT APPROACH

Planning for and designing a comprehensive approach to stakeholder engagement is integral for successful developments. This includes considering the broader context of engagement as well as the practical aspects of a specific MRE project. Recommendations for developing engagement approaches for MRE include:

- **Tailoring engagement for each project based on different contexts, communities, or locations.** To identify what the needs are, stakeholders and target audiences should be defined from the beginning of project planning and reevaluated throughout the different project phases.
- **Clarifying responsibility and setting expectations, including defining who is responsible for which aspects of engagement and setting goals and ideal outcomes of engagement efforts.** This includes communicating expectations as well as possible limitations, particularly to avoid negative outcomes – such as disappointment or frustration from stakeholders – and creating and implementing an engagement plan based on human and financial resources. It is best to identify who will be most successful to lead engagement activities within a community, ideally someone with specific expertise and training (facilitation, community outreach, public participation, communications, etc.). This could be the project developer or a third party, such as a facilitator/mediator, local representative, or other honest broker.
- **Conducting stakeholder engagement and information sharing activities early and regularly, ideally prior to key decisions being made to allow for stakeholder input to be incorporated, or changes made based on suggestions or concerns.** Taking this approach shows commitment to creating a project that works with and for a community, allowing

communities and stakeholders to feel listened to and heard, to indicate the value of their feedback and influence on the project. Engagement or consultation fatigue should be acknowledged and efforts should be made to reduce burdens on stakeholders, such as coordinating activities with other engagement processes, learning from past development projects to avoid repeating what has already been done, and assuring that people feel their time engaging is well spent.

- **Moving beyond informing to participatory approaches that build trust and listen to stakeholders and communities.** There is a need to familiarize the public with MRE technologies and the project, but the priority should be listening and understanding perspectives. A well-planned approach should include transparency and consistency, as well as building and maintaining long-term relationships, and seeking to move toward incorporating stakeholders in decision-making, co-design, and community empowerment. Aiming for openness, collaboration, and the use of participatory methods in stakeholder engagements results in an empowered community that can actively take part in local energy transitions.
- **Including equity and social and energy justice considerations throughout engagement and in all project phases—planning, development, implementation, operation, and decommissioning.** This includes identifying barriers to justice, equity, and accessibility at each phase and implementing adequate solutions to mitigate the barriers.

5.5.2. IMPLEMENTATION OF GUIDANCE FOR MRE

There is a plethora of guidance available on stakeholder engagement, though studies have shown that even when good practices are identified, they are not always followed (Cronin et al. 2021). Guidance from across industries on stakeholder engagement should be applied to MRE, but there is a need for more complete guidance specific to MRE. Regulations established at the national level often include requirements for consultation but lack guidance for comprehensive stakeholder engagement and consideration for the uniqueness of local contexts and project details. Many of these regulations apply to large-scale infrastructure projects broadly, or offshore renewable energy in general (typically focusing on offshore wind), and as such may not be the best fit for MRE. Having regulatory-based guidance for MRE that goes beyond consultation will help provide industry-specific information on the best approaches for specific jurisdictions. Revisiting and expanding this guidance as the industry moves to larger-scale developments will become increasingly important, as will learning from industries like offshore wind that deploy at larger scale. This will require significant coordination across sectors of industry, government, and research.

5.5.3. INCREASE KNOWLEDGE BASE FOR MRE AND SHARE LESSONS LEARNED

As more MRE projects are deployed, the stakeholder engagement knowledge base is growing, incorporating learning from other marine-based engagement processes such as offshore wind, aquaculture, or marine spatial planning. As MRE-specific knowledge and insight are gathered, moving to recommendations specific to the MRE industry will help develop an engagement that best fits this unique context.

Although the knowledge base of successful engagement efforts is growing, there is a noticeable gap in the literature describing post-deployment efforts and ongoing assessments. Much of the available literature for MRE focuses on identifying stakeholders or guidance and information from the perspectives of developers. To be able to truly analyze stakeholder engagement within the MRE industry, there is also a need for ongoing and post-engagement research on stakeholder and community perspectives. This will inform whether engagement efforts can be deemed successful from all standpoints and point towards improvements and increased understanding of how engagement should be carried out for MRE. This research could best be carried out by researchers and is likely to require government support by way of directives and/or funding.

The recommendations listed in this section will help progress MRE stakeholder engagement. As examples of engagement efforts continue to be shared and further insights gathered and documented, improvements can be made to the approaches used and best practices for the MRE industry can be identified. Working across institutional or national boundaries toward successful, inclusive, and collaborative stakeholder engagement will provide benefits for individual projects, for the MRE industry as a whole, and for communities and stakeholders surrounding those projects.

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Suggested citation:

Rose, D. J., and Freeman, M. C. 2024. Stakeholder Engagement for Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 144-169). doi:10.2172/2438593

Section D

RESOURCES TO ADVANCE MARINE RENEWABLE ENERGY

6.0

Strategies to Aid Consenting Processes for Marine Renewable Energy

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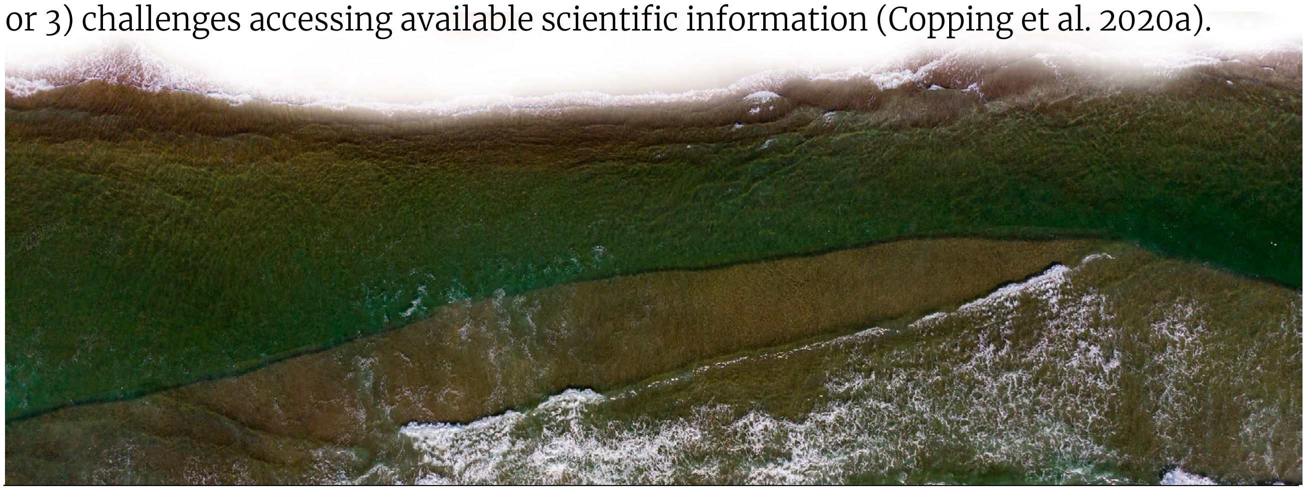
While the marine renewable energy (MRE) industry has made positive strides in the past decade, challenges remain that stall forward progress, scaling up, and commercialization. For MRE to provide a viable solution to address the effects of climate change and achieve sustainable development and renewable energy goals, identifying and understanding barriers and opportunities to deployment is key. Barriers to date have included long consenting timelines, costly in-depth baseline data collection and monitoring requirements, and hesitancy in some countries to approve device and array deployments (Copping & Hemery 2020; Kramer et al. 2020). Some of the key drivers behind these barriers are 1) uncertainty about potential effects of MRE on marine animals, habitats, and the environment; 2) lack of familiarity with MRE technologies; or 3) challenges accessing available scientific information (Copping et al. 2020a).



For example, PacWave South in Oregon, the United States' (US) first pre-permitted commercial-scale, open-ocean wave energy test site navigated an almost 10-year process to receive authorization and dealt with uncertainty about environmental effects that might be caused by devices to be tested in future (Freeman et al. 2022). In another instance, Sustainable Marine Energy Canada Ltd. faced challenges in achieving consent for a tidal energy array at the Fundy Ocean Research Centre for Energy (FORCE) test site in the Minas Passage, Bay of Fundy, which ended with the company choosing to not move forward with its efforts in Canada (Chandler 2024). This decision was primarily driven by regulatory uncertainty about how to manage collision risk to fish. Opportunities to address these barriers and reduce uncertainty include deploying devices at test centers to collect data, share lessons from early developments that can be applied to new projects to reduce onerous baseline data collection and monitoring requirements, and decrease uncertainty through coordinated strategic research and monitoring funded by governments. For example, deployments at the European Marine Energy Centre's (EMEC) test sites in the United Kingdom (UK) have paved the way for tidal and wave energy devices to deploy, monitor, and learn as they go. Pre-and post-installation monitoring data on seabed habitat change at the Voith Hydro HyTide installation at EMEC were used to support consenting at the Brims Tidal Array in Orkney, Scotland, UK. The data indicated that there were minimal impacts on the seabed habitats from foundation drilling and allowed the Brims Tidal Array to adopt a proportionate approach for the environmental impact assessment (EIA), allowing focus on areas of concern with greater uncertainty (Copping et al. 2020a).

Several approaches have been used around the world to support consenting for MRE devices, learn from each development, set precedents that can reduce long timelines for consenting, ease burdensome or disproportional requirements for baseline data collection and monitoring, and advance the industry as a whole. The sections in this chapter provide examples of the strategies, processes, and tools that can aid consenting by examining environmental effects of MRE. This chapter builds on the information presented in Copping et al. (2020a), Le Lièvre (2020), and O'Hagan (2020) to describe updates to processes including risk retirement and data transferability, adaptive management (AM), and marine spatial planning (MSP), as well as how these approaches have been used to support the sustainable development of the MRE sector. The information in Le Lièvre (2020) and O'Hagan (2020) is still largely accurate for AM and MSP, so this chapter focuses on providing brief background and updates since 2020. As such, the majority of this chapter focuses on Ocean Energy Systems (OES)-Environmental's risk retirement and data transferability approaches. This includes OES-Environmental resources and tools such as the guidance documents for risk retirement, monitoring datasets discoverability matrix, and management measures tool. Each section in this chapter begins with a brief overview of information from the *2020 State of the Science* report (Copping et al. 2020a; Le Lièvre 2020; O'Hagan 2020) followed by updates and examples of these approaches from the international MRE industry, and ends with examples of specific tools developed to aid consenting for MRE.

6.1. RISK RETIREMENT AND DATA TRANSFERABILITY

Risk retirement and data transferability have been used in other industries (health, transportation, land management, etc.) including MRE (Bridge et al. 2020; Drummond et al. 2009; Gransberg et al. 2018; ORJIP Ocean Energy 2022a; Robertson et al. 2018; Václavík et al. 2016), though often the application of these processes is not identified using these terms, or more commonly is not well documented and disseminated. For example, risk retirement is similar to the concept of a Proportionate EIA used in the UK (IEMA 2017).

Risk retirement for MRE, as defined by Copping et al. (2020a), aims to reduce barriers to consenting MRE developments by:

- Increasing the accessibility of existing scientific information and use of this information through data transferability;
- Providing an approach to assess risk and determine the ability to retire risks where evidence shows the level is low;
- Offering guidance to distinguish between perceived (but unknown) and actual risks, and to apply current information and data to consenting processes; and
- Identifying which risks remain uncertain or undetermined, requiring more research to increase understanding.

WHAT IS RISK RETIREMENT?

A process for facilitating consenting for MRE developments whereby each potential environmental risk need not be fully investigated for every project. Instead, regulators, advisors, developers, and consultants can rely on what is known from consented MRE projects, related research studies, or findings from analogous offshore industries to help determine which interactions are better understood and can be considered retired or low risk. If new information becomes available, a retired risk can (and should) be re-examined and a new decision made about risk retirement.

This process aims to distinguish between perceived and actual risk, provide assistance for regulatory decision-making, and inform the MRE community what is likely to be required for consenting MRE projects.

Risk retirement does not take the place of any existing regulatory processes or replace the need for appropriate data collection before, during, and after MRE device deployment.

(Copping et al. 2020a)

The risk retirement process is offered for regulators and advisors to assist with decision-making throughout consenting processes and for developers and consultants as they prepare applications for MRE developments.

Copping et al. (2020a) offer in-depth information on risk retirement and data transferability, as developed by OES-Environmental, with feedback from regulators and advisors in OES-Environmental countries and throughout the international MRE community. These processes and associated tools aim to compile existing scientific information on environmental effects of MRE into formats that are easily accessible and applicable for consenting and licensing MRE developments to help satisfy regulatory requirements and increase understanding (Figure 6.1). A risk retirement pathway was created to determine the level of risk for potential stressor-receptor interactions (see Chapter 3). The pathway has a series of steps to assess if an interaction can be retired, highlight solutions based on available evidence, and chart a proportionate approach to identifying gaps in knowledge. A data transferability process was also developed, including a framework for its application, guidance for data collection consistency, best management practices, and an online tool—the monitoring datasets discoverability matrix—for discovering analogous datasets. Other components include evidence bases (see Section 6.1.1.), a management measures tool to inform the use of management (or mitigation) measures when effects may be uncertain, and guidance documents for risk retirement which bring together risk retirement, evidence bases, and associated tools to guide application for consenting (see Section 6.1.2.). Additional resources, like the brochure MRE: An Introduction to Environmental Effects, created for regulators or those new to the industry, are provided as an introduction to environmental effects of MRE, and are also available.

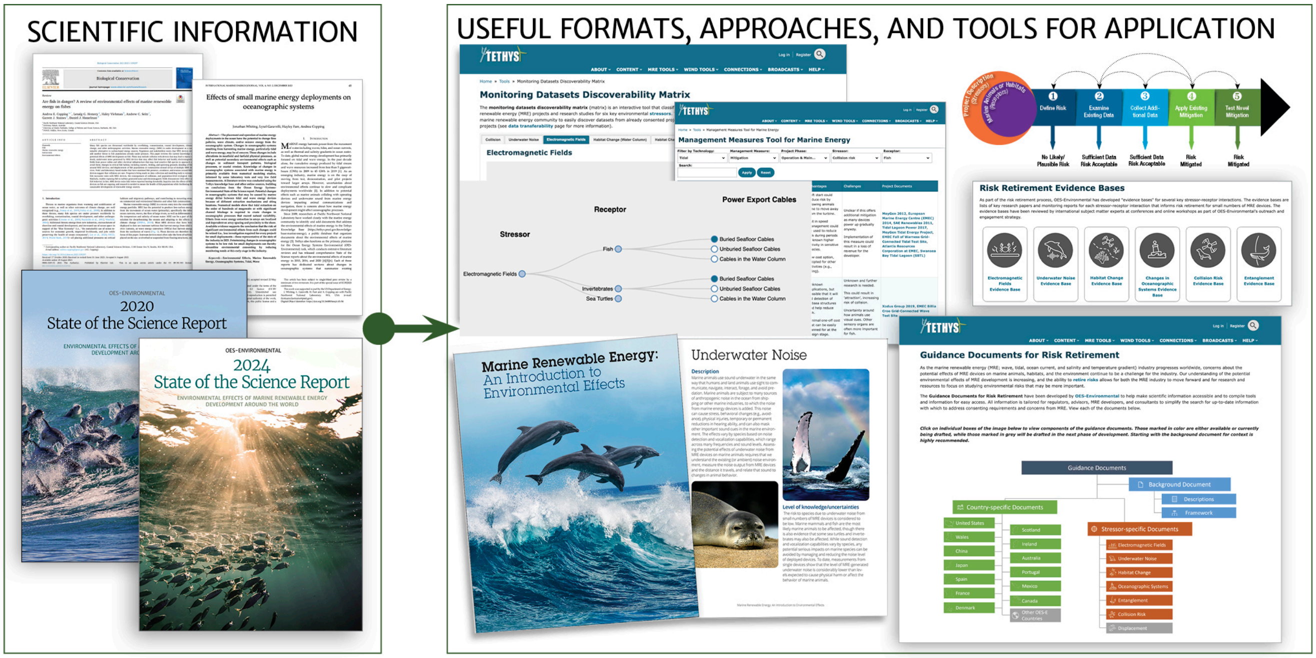


Figure 6.1. Depiction of the process to move from available science on environmental effects of marine renewable energy (MRE) to application for consenting processes. Information including Ocean Energy Systems (OES)-Environmental's *State of the Science* reports, existing data and information from MRE developments, and peer-reviewed literature on environmental effects of MRE are compiled and organized into formats useful for specific audiences or contexts.

6.1.1. ASSESSING ENVIRONMENTAL INTERACTIONS FOR RISK RETIREMENT

During 2019-2020, OES-Environmental identified two stressor-receptor interactions, electromagnetic fields (EMFs) and underwater noise, as candidates for risk retirement for small numbers of devices (Copping et al. 2020a). Evidence bases were created for each of these interactions, consisting of key documents that best inform the evaluation of the state of understanding and risk level. These documents include journal articles, research papers, and monitoring reports primarily from the US, European Union, UK, and Canada. For risk retirement purposes, the available environmental effects information applies to small numbers of devices (about one to six) and primarily to full-scale (or close to full-scale) devices. While MRE devices vary in size and configuration—with some creating large amounts of power, while others generate less—the available studies do not provide much guidance on how to estimate the incremental risk based on these differences.

Grounded by the available evidence bases, experts and practitioners in the MRE community were consulted to evaluate risk retirement. Consensus was reached to accept the evidence for risk retirement of both interactions for small numbers of devices, with some caveats and additional data collection needs identified (Copping et al. 2020a; Copping et al. 2020b). For example, needs for underwater noise include a library of standardized noise measurements from individual MRE device types and models and *in situ* noise measurements for new devices deployed using the International Electrotechnical Commission (IEC) Technical Committee 114 Level B recommendations (Copping et al. 2020a; Copping et al. 2020b; International Electrotechnical Commission 2019a). For EMFs, while implementing management measures such as burying cables helps satisfy some regulatory concerns, remaining data gaps and needs include developing reliable EMF sensors, collecting field data to validate and improve numerical models, and creating regulatory thresholds for EMFs (Copping et al. 2020a; Copping et al. 2020b; Hasselman et al. 2023).

Since 2020, three additional stressor-receptor interactions have been identified as candidates for risk retirement for small numbers of devices: changes in habitat, changes in oceanographic systems, and entanglement. Beyond these, other environmental interactions require additional strategic research, such as collision risk and displacement. Table 6.1 provides a summary of risk retirement for each stressor-receptor interaction, based on available data and information. Each of these interactions is addressed in further detail in Chapter 3.

Table 6.1. Overview of risk retirement for each stressor-receptor interaction based on evidence bases and feedback from Ocean Energy Systems (OES)-Environmental international workshops and consultations with experts. For each interaction, evidence bases provide citations and references for understanding the level of risk. Small numbers of devices are generally considered between one to six devices.

STRESSOR-RECEPTOR INTERACTION	READINESS FOR RISK RETIREMENT
Collision risk	Need more information.
Underwater noise	Retired for small numbers of devices. May need to revisit as the industry moves to larger-scale arrays.
Electromagnetic fields	Retired for small numbers of devices. May need to revisit as the industry moves to larger-scale arrays.
Changes in habitat	Retired for small numbers of devices. May need to revisit as the industry moves to larger-scale arrays.
Oceanographic systems	Retired for small numbers of devices. May need to revisit as the industry moves to larger-scale arrays.
Entanglement	Need more information as the industry moves to larger-scale arrays.
Displacement	Need more information as the industry moves to larger-scale arrays.

CHANGES IN HABITAT

Evidence from monitoring around single MRE devices, field research, and information from other marine industries indicate that impacts from changes in habitat are limited and unlikely to cause harm to marine animals and the environment (Hemery 2020; Hemery et al. 2021; OES-Environmental 2022a). Based on the available literature, consultation with the MRE community, and evaluation of risk retirement, there is consensus among experts that for small-scale developments, the risk of changes in habitats can be retired if such developments are properly sited to avoid sensitive or unique habitats.

CHANGES IN OCEANOGRAPHIC SYSTEMS

Evidence from field measurements and numerical modeling suggests that for single devices and small arrays, changes in oceanographic systems will not be detectable above the natural variability in ocean conditions at a site (OES-Environmental 2022b; Robins et al. 2014; Whiting et al. 2023; Yang et al. 2013). There is consensus among experts that for small-scale developments the risk can be retired. As the industry scales up, this risk will need to be reassessed to better understand impacts from large-scale arrays, to study cumulative impacts from these and other marine developments, and to address remaining uncertainties.

ENTANGLEMENT

MRE device mooring lines have no loose ends and are maintained taut during operation and under sufficient pressure to prevent a loop from forming that can entangle large marine animals. Due to these characteristics and the mass and size of mooring lines and cables used in MRE developments, the risk of entanglement is considered low or non-existent for single devices and small arrays (OES-Environmental 2023). Some stakeholders have concerns that derelict fishing gear or other marine debris could be caught on mooring lines or cables, posing a secondary entanglement risk to marine animals. However, this risk has never been demonstrated and can likely be mitigated by periodic visual inspection and removal of such materials.

6.1.2. GUIDANCE DOCUMENTS FOR RISK RETIREMENT

Guidance documents that make scientific information readily available, compile tools and information for easy access, and provide a framework for application have been developed by OES-Environmental to apply risk retirement during consenting processes (Figure 6.2) (Copping et al. 2021; Freeman et al. 2024). These documents are tailored for regulators, advisors, developers, consultants, and other stakeholders, and have been written to be generally applicable internationally. They include:

1. A background document that provides an overview of risk retirement and the guidance documents, descriptions of four regulatory categories relevant for MRE consenting—species and populations at risk, habitat loss or alteration, effects on water quality, and effects on social and economic systems—and how they map to key stressor-receptor interactions, and a framework for how to apply risk retirement and data transferability within consenting processes;
2. Stressor-specific documents that provide an overview of the state of knowledge for each stressor-receptor interaction, links to existing data and information, a description of risk retirement, and recommendations to advance understanding; and
3. Country-specific documents that provide an overview of the MRE regulatory context within each OES-Environmental country.

6.1.3. DATA TRANSFERABILITY

As more MRE devices are deployed with baseline assessments and post-installation monitoring, available data and information on potential environmental effects will increase, improving the knowledge base to inform future MRE developments and the risk retirement process. Leveraging existing information through data transferability—the application of existing learning, analyses, monitoring data, and information from one project, jurisdiction, or country to another—can help lead to more efficient environmental consenting processes (Copping et al. 2020a; Kramer et al. 2020). Collecting data in a consistent manner will support the transfer of data and comparison of results

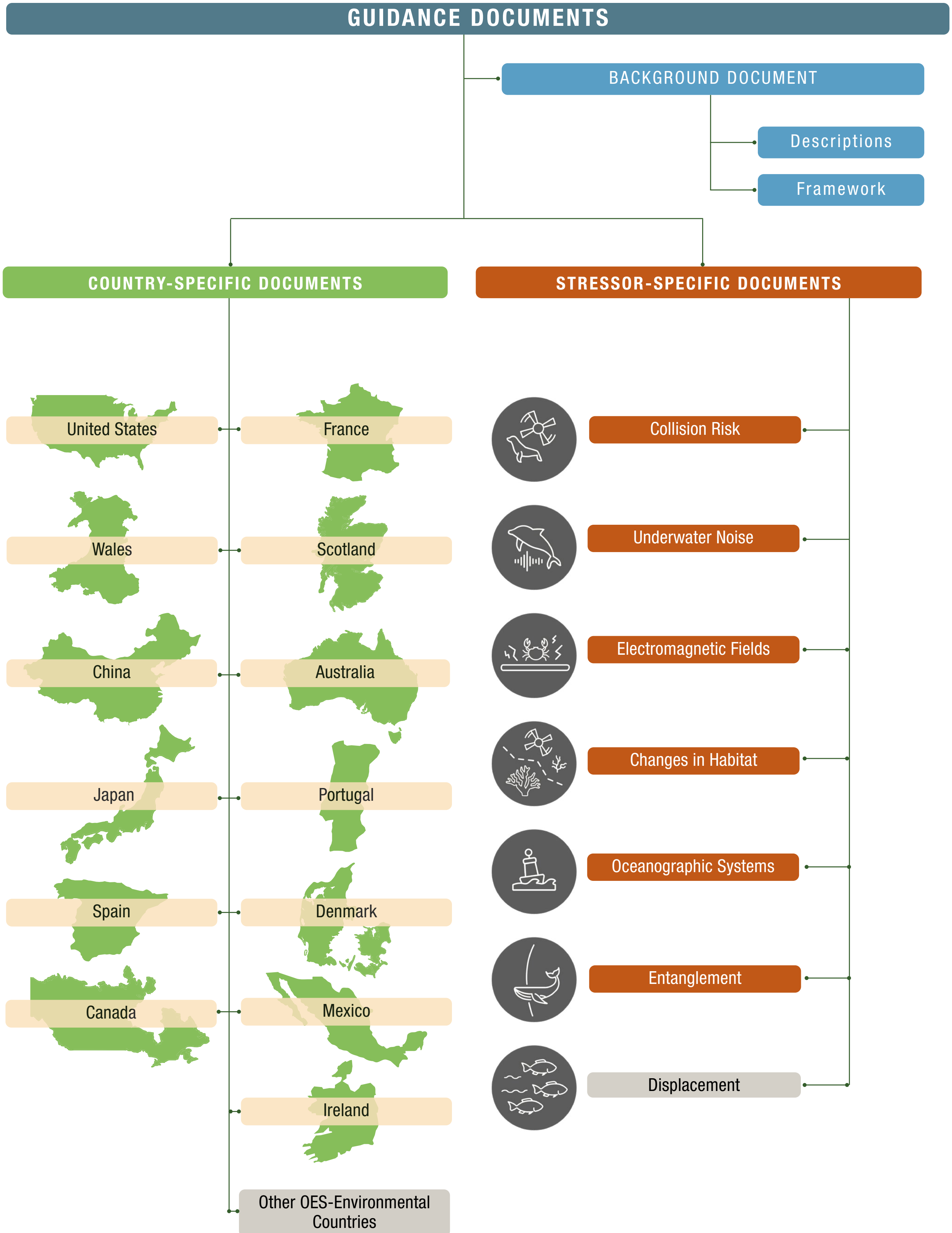


Figure 6.2. Overview of the guidance documents for risk retirement. Colored boxes indicate completed guidance documents. Boxes in grey indicate next steps in the development of the guidance documents. Each of the individual guidance documents can be accessed via the links in the figure.

among MRE projects. Eaves et al. (2022) highlight the lack of standards for environmental monitoring and identify monitoring technologies and methods that will result in consistent data collection for four key stressor-receptor interactions, and ultimately assist with data transferability. Recommendations for monitoring collision risk, underwater noise, EMFs, and changes in benthic habitat are detailed in Staines et al. (2022), Haxel et al. (2022), Grear et al. (2022), and Hemery et al. (2022), respectively.

Data transferability hinges on the accessibility of applicable datasets that are relevant for new MRE developments. At the request of regulators, OES-Environmental developed a monitoring datasets discoverability matrix (matrix) to catalog and easily identify available and relevant datasets to be used to transfer learning and information. The matrix is structured by key stressor-receptor interactions and includes characteristics for each interaction to define similar attributes for transfer (Figure 6.3). These characteristics can be selected from

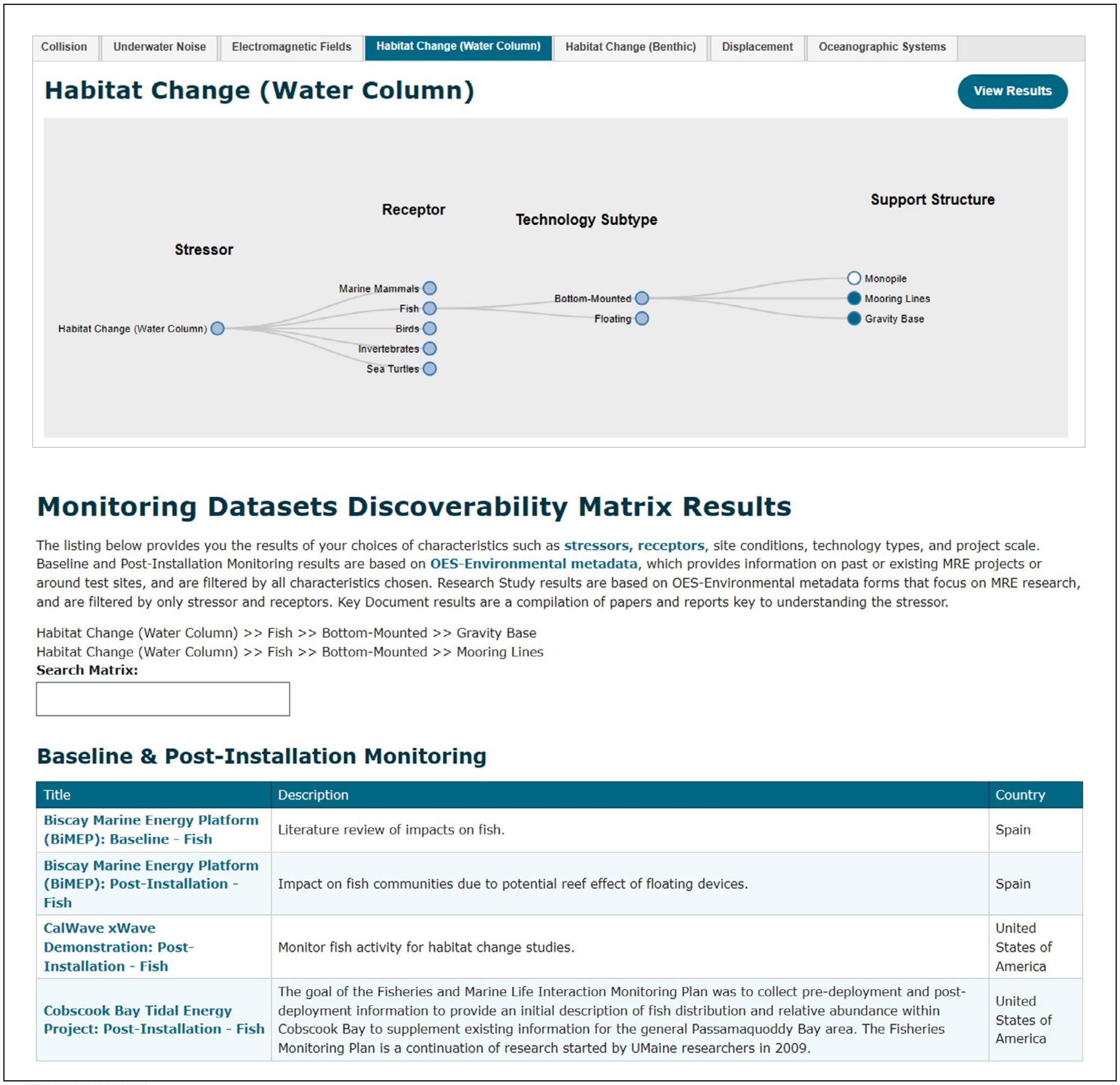


Figure 6.3. Example of the monitoring datasets discoverability matrix (matrix) for changes in habitat within the water column, including the characteristics related to this stressor-receptor interaction and results from the matrix query. This example shows baseline and post-installation monitoring but does not show additional matrix results including research studies from change to: Ocean Energy Systems (OES)-Environmental's metadata collection as well as key documents from the changes in habitat evidence base.

the matrix to discover available data and information from MRE and analogous industries (e.g., offshore wind, offshore oil and gas) that can be used to inform consenting and understanding of new MRE projects.

Using the best practices for data transfer described in Copping et al. (2020a) and the matrix can help the MRE community transfer data and information gained from past and current projects to inform future developments, with the aim of easing requirements for baseline data collection and monitoring.

6.1.4. CASE STUDIES OF RISK RETIREMENT AND DATA TRANSFERABILITY

The principles of risk retirement and data transferability have been implemented in the MRE industry, but often are not documented or identified as "risk retirement". Sharing examples of how MRE projects have employed these processes can help to build confidence in their application for future projects. This section highlights eight case studies from the MRE industry where risk retirement, as well as data transferability, have occurred. At the end of each case study, a summary table details how each MRE development navigated potential risk, matched to the steps in the risk retirement pathway (Figure 6.4).

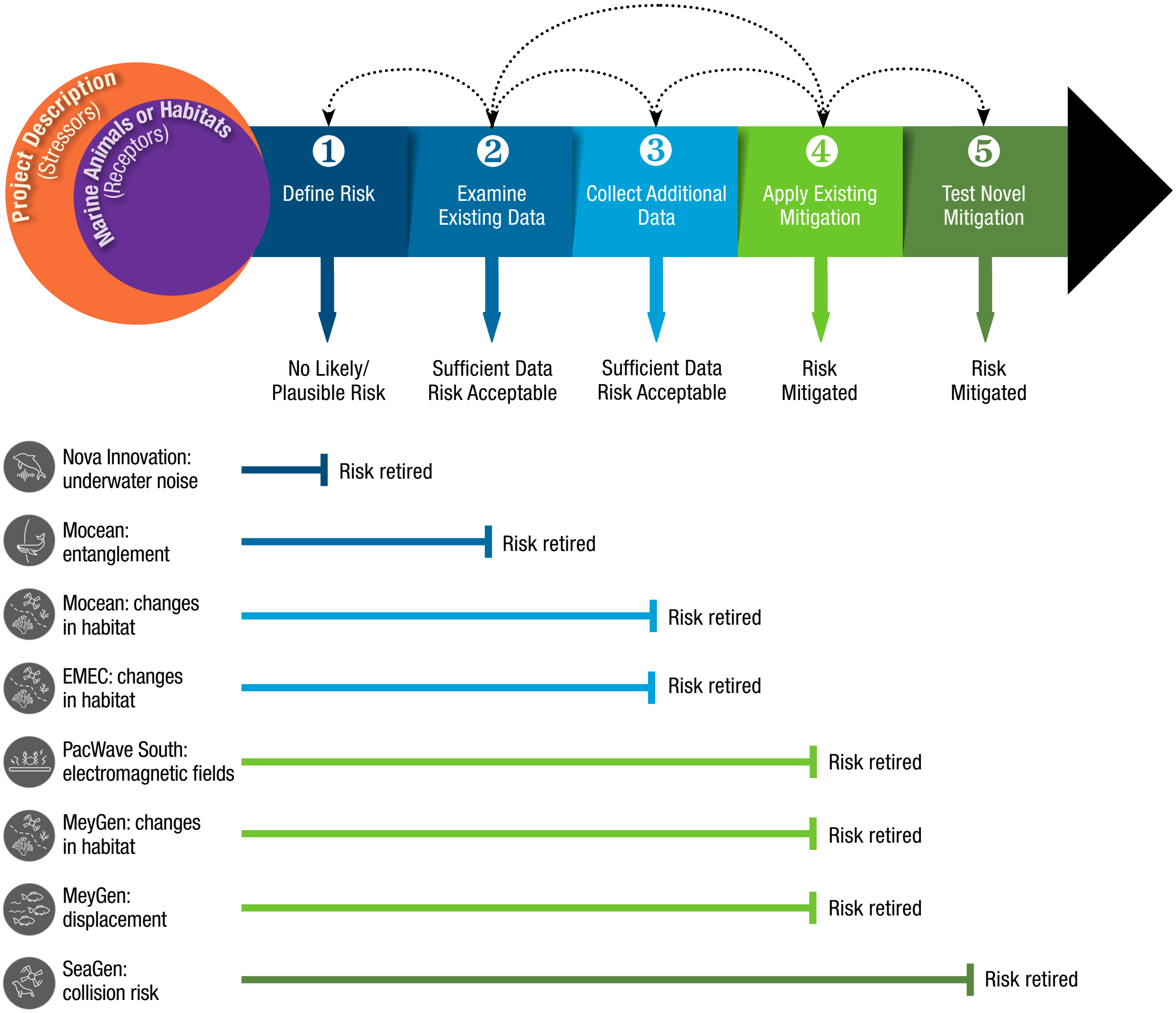


Figure 6.4. Risk retirement pathway demonstrating its use in eight case studies. The colored lines below the risk retirement pathway demonstrate the applicability of each MRE development to steps in the pathway, and where risk retirement was achieved. EMEC = European Marine Energy Centre.

NOVA INNOVATION SHETLAND TIDAL ARRAY – UNDERWATER NOISE

Contributed by Kate Smith (Nova Innovation)

Project Description: Operational 0.6 MW project in Bluemull Sound, Shetland, Scotland (Figure 6.5), comprised of six, two-bladed, 100 kW horizontal axis turbines on seabed gravity support structures. Three of the turbines are Nova Innovation's original geared design and three are next-generation direct drive (gearless) turbines. The turbines are connected to the main Shetland grid and have been powering residences since 2016, and electric cars through a vehicle charging point since 2018.

Stressor-receptor interaction: Underwater noise from operational turbine resulting in injury or behavioral responses (disturbance or displacement) in key sensitive species such as marine mammals.

Pathway to risk retirement: A detailed quantitative noise assessment was not required by Marine Scotland (now Marine Directorate) or NatureScot (previously Scottish Natural Heritage) for Nova Innovation's license applications for the Shetland Tidal Array, due to the small size and number of turbines (Marine Scotland 2024; Smith 2024). Land-based bird and mammal surveys and turbine-mounted subsea cameras used as part of Nova Innovation's adaptive Project Environmental Monitoring Plan have demonstrated that the project had not resulted in any disturbance or displacement of marine mammals from Bluemull Sound (see Nova Innovation case study in Section 6.2.2).

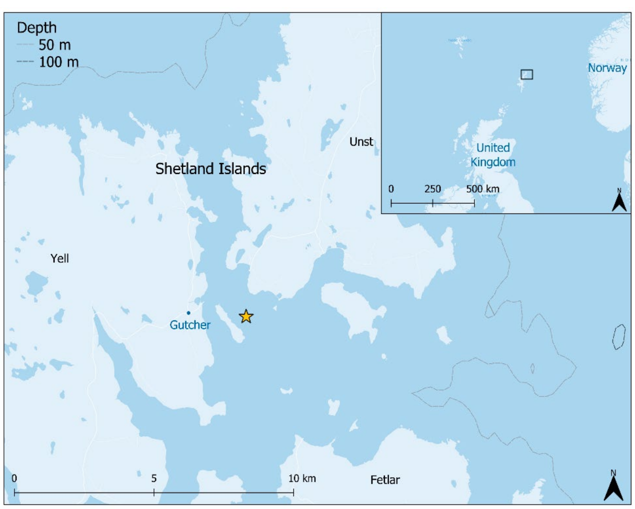


Figure 6.5. Location of the Nova Innovation Shetland Tidal Array in Scotland, United Kingdom (yellow star).

The assessment of subsea noise is likely to become an increasingly important part of consenting tidal energy projects as they increase to commercial scale. In recognition of this, Nova Innovation worked with Offshore Renewable Energy Catapult to measure the noise generated by the turbines in the Shetland Tidal Array to de-risk consenting of future projects.

The work was undertaken when all six turbines were installed and operating in Bluemull Sound[1], and showed that even prolonged exposure of sensitive species at close range to Nova Innovation's turbines is not likely to result in injury, based on established thresholds for sound pressure levels (Southall et al. 2019). Some localized behavioral response (evasion) close to the turbines may occur; this evasion may help to reduce collision risk for turbines.

Conclusion: The risk of injury or behavioral responses from underwater noise was retired for the Shetland Tidal Array based on the small size and number of turbines. A detailed qualitative noise assessment was not required by Marine Scotland or NatureScot for consenting, and no noise monitoring was required during the operational phase of the project.

Summary of risk retirement:

DEFINE RISK

- Underwater noise from operational turbine resulting in injury or behavioral responses in key sensitive species such as marine mammals.
- The characteristics of the project were defined, and due to the small size and number of turbines a detailed quantitative noise assessment was not required for the license application.

1. The three geared turbines were in situ at the time of the work detailed in this case study but were decommissioned in 2023.

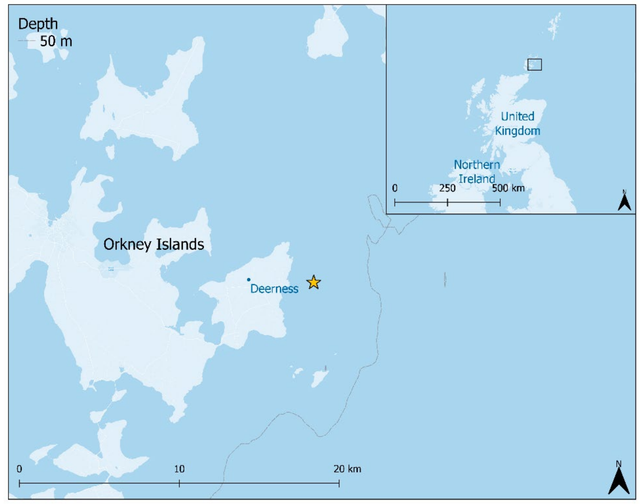


Figure 6.6. Location of the Mocean Energy in Scotland, United Kingdom (yellow star).

MOCEAN ENERGY – ENTANGLEMENT

Contributed by Shane Quill (Aquatera Ltd.) and Jon Clarke (Mocean Energy)

Project Description: One wave energy converter (WEC) system (BlueX) off the coast of Orkney (east of Deerness), Scotland (Figure 6.6) with an umbilical and associated mooring lines, covering a small footprint (0.05 km^2) (Marine Scotland, 2023, 2019a).

Stressor-receptor interaction: Risk of entanglement in mooring lines or cables for cetaceans and basking sharks (*Cetorhinus maximus*).

Pathway to risk retirement: NatureScot conducted a study of entanglement risk in 2014, which concluded that MRE mooring lines are unlikely to pose a major entanglement threat to cetaceans and basking sharks as they have too much tension to create a loop and do not have loose ends (Benjamins et al. 2014). The study notes that while there is a greater risk of entanglement for large baleen whales (e.g., fin whale, *Balaenoptera physalus,* or humpback whale, *Megaptera novaeangliae*) due to their large size and feeding behavior (Benjamins et al. 2014), the likelihood of their occurrence at the proposed deployment site was considered very low, and humpback whales in particular are rare visitors to Orkney waters (Evans et al. 2011).

Conclusion: Using this available baseline information and the technical project information, an assessment of the risk posed by the presence of a single WEC, umbilical, and two associated taut mooring lines with a relatively small footprint, concluded that there was no significant entanglement risk for cetaceans or large baleen whales (Aquatera Ltd 2021). A commitment to reporting any notable entanglement events to the regulator within 24 hours of observation was included in the project mitigation and monitoring plan (Aquatera Ltd 2021).

Summary of risk retirement:

DEFINE RISK

- Risk of entanglement in mooring lines or cables leading to injury or death of large cetaceans and basking sharks.

EXAMINE EXISTING DATA

- A government-commissioned study concluded that mooring lines associated with MRE devices are unlikely to pose a major threat of entanglement risk to cetaceans and basking sharks (Benjamins et al. 2014).
- A relative risk assessment for entanglement was undertaken as outlined in Benjamins et al. (2014). This confirmed that species of most concern (large baleen whales) were not in the area of the deployment and therefore not an issue.

MOCEAN ENERGY – CHANGES IN HABITAT

Contributed by Shane Quill (Aquatera Ltd.) and Jon Clarke (Mocean Energy)

Project Description: One WEC system (BlueX) off the coast of Orkney (east of Deerness), Scotland (Figure 6.6) with an umbilical and associated mooring lines, covering a small footprint (0.05 km^2) (Marine Scotland 2023, 2019a).

Stressor-receptor interaction: Changes to benthic habitats and species during installation of the mooring system.

Pathway to risk retirement: At the license application stage, the mooring system consisted of a combination of nylon and chain mooring lines and associated clump weights. No drilling was proposed for the mooring system installation, therefore potential disturbance from the installation was considered highly localized and temporary in nature.

A study commissioned by NatureScot in 2011 concluded that "sublittoral sand biotopes... are of widespread occurrence throughout Scotland and the UK and at least surface observation of the sediment suggests impoverished faunas, especially in the highly mobile sediments of the southwestern region of the Pentland Firth" (Moore & Roberts 2011). A benthic survey carried out in 2019 by the project team confirmed that the deployment area was consistent with the previous survey conducted by NatureScot (Aquatera Ltd 2021), which reported the presence of sublittoral sand biotope to the east of Holm Sound where there were few signs of infaunal life and a sparse epifaunal community mainly composed of widely scattered echinoderms. The assessment concluded that due to the nature of the proposed work and the mooring system, potential disturbance was considered to be highly localized and temporary in nature. No specific mitigation was proposed in relation to this impact during the deployment and operation of the BlueX WEC system.

Conclusion: The presence of a single WEC and associated mooring system was anticipated to result in minimal disturbance of sensitive/protected habitats at the deployment site (Marine Scotland 2019, 2023).

Summary of risk retirement:

DEFINE RISK

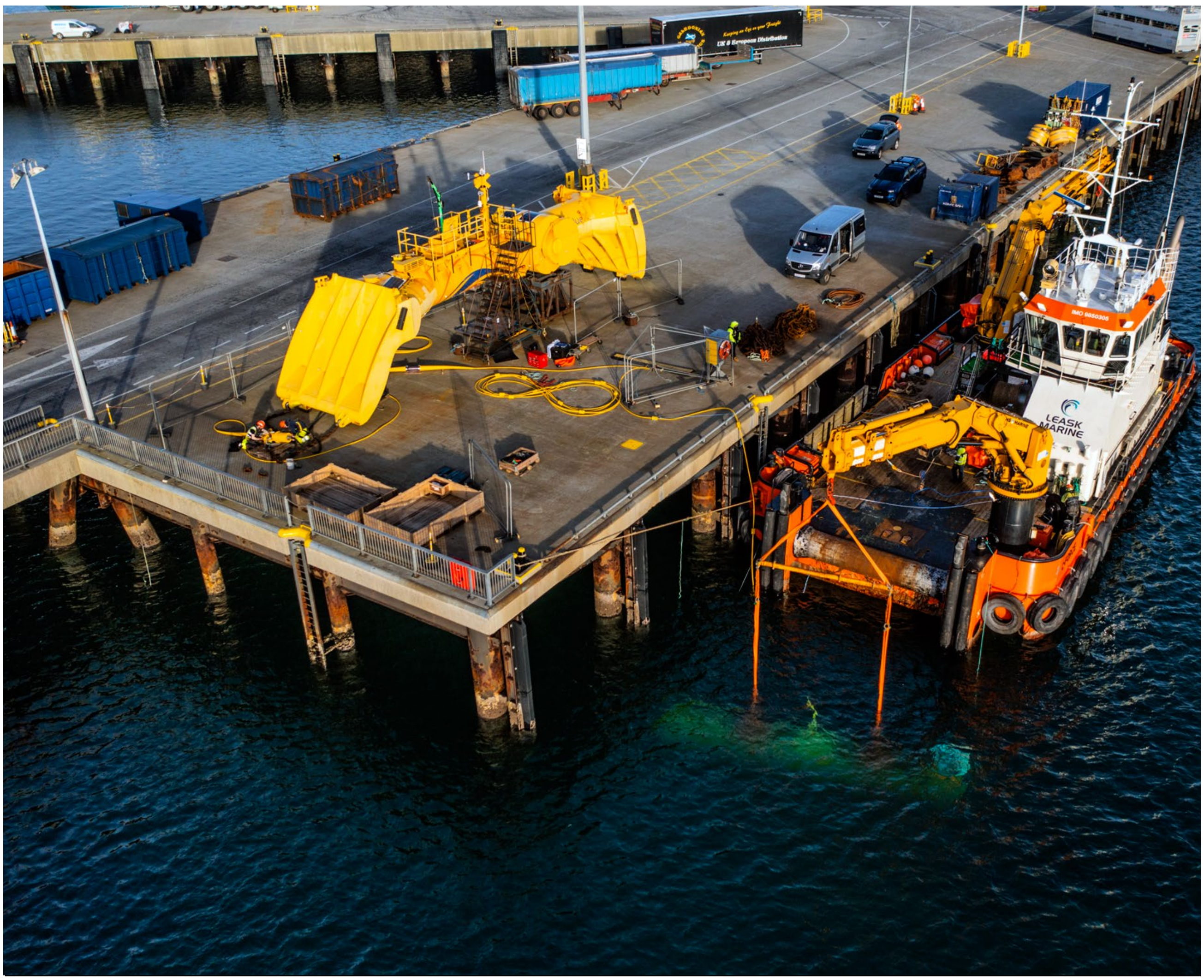
- Risk of benthic habitat disturbance from installation of the mooring system.

EXAMINE EXISTING DATA

- A government-commissioned study confirmed that the wider geographic area did not contain protected or sensitive habitats (Moore & Roberts 2011).

COLLECT ADDITIONAL DATA

- A further project-specific survey was conducted to confirm the findings of the government-commissioned study (Aquatera Ltd 2021).
- Disturbance of sensitive/protected habitats was considered to be limited (highly localized and temporary in nature), therefore no specific mitigation was proposed.



EMEC, FALL OF WARNESS TIDAL TEST SITE AND BILLIA CROO WAVE TEST SITE – CHANGES IN HABITAT

Contributed by Ian Hutchison and Jennifer Fox (Aquatera Ltd.)

Project description: Grid-connected test sites off the coast of Orkney, Scotland at EMEC (Figure 6.7) for testing and demonstration of large-scale tidal and wave energy technologies in the open ocean.

Stressor-receptor interaction: Changes to benthic habitats.

Pathway to risk retirement: Baseline benthic surveys were undertaken during the EIA process for the Fall of Warness and Billia Croo test sites in 2002 and 2005, respectively (Carl Bro Group Ltd 2002; Foubister 2005). Developers planning to deploy and test their wave or tidal device at either of these sites were required to prepare an Environmental Mitigation and Monitoring Plan, which in most instances, included a commitment to undertake pre- and post-installation and post-decommissioning benthic surveys. Following a review by the EMEC Monitoring Advisory Group in 2012, the regulator (Marine Scotland) issued a communication that benthic surveys would no longer be required under license conditions due to the sufficiency of previously collected data (Marine Scotland 2013a).

Conclusion: Based on available and collected data, no significant effects on benthic habitats from installation, operation, and removal of wave and tidal devices were observed. As such, the licensing requirement to undertake pre- and post-installation and post-decommissioning benthic surveys was removed (Marine Scotland, 2013a).

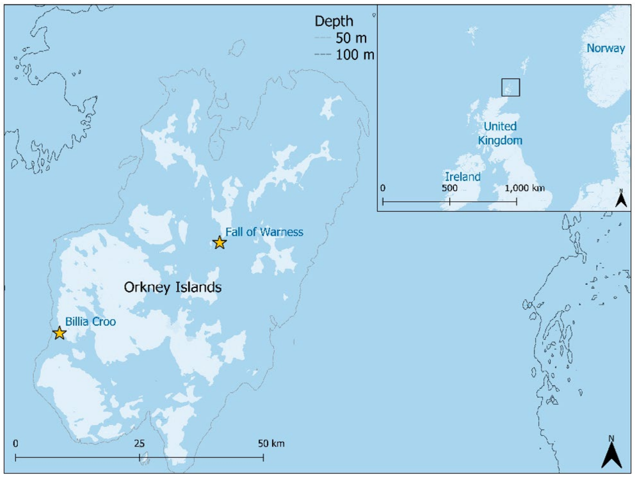


Figure 6.7. Locations of European Marine Energy Centre (EMEC) test sites (Billia Croo and Fall of Warness) in Scotland, United Kingdom (yellow stars).

Summary of risk retirement:

DEFINE RISK

- Risk of benthic habitat change from installation, operation, and removal of large-scale wave and tidal energy devices.

EXAMINE EXISTING DATA

- For the Fall of Warness tidal test site, benthic survey data were collected as part of the original EIA by Aquatera (Foubister 2005).
- For the Billia Croo wave test site, an underwater survey (still images and video), a sediment core survey, and a littoral survey were carried out by Heriot-Watt University's International Centre for Island Technology (Carl Bro Group Ltd 2002).

COLLECT ADDITIONAL DATA

- Developers were required to undertake site-specific pre- and post-installation and post-decommissioning benthic surveys.
- As no significant effects were observed with the additional data collected, benthic surveys were no longer required under license conditions.

MEYGEN TIDAL ENERGY PROJECT – CHANGES IN HABITAT

Contributed by Jennifer Fox and Ian Hutchison (Aquatera Ltd.), and Ian M. Davies (Carronside Consultancy Ltd.)

Project description: MeyGen is a large commercial-scale tidal array development off the north coast of Scotland (Figure 6.8). MeyGen was awarded an 'agreement for lease' from the UK Crown Estate in 2010, to develop a tidal array up to 398 MW. Phase 1 of the project was granted planning consent from Scottish Ministers for up to 86 MW (or 61 tidal turbines) in 2013 (Marine Scotland 2013b). The first stage of the project (Phase 1A) was limited to the installation and operation of six turbines, with expansion subject to the findings from environmental monitoring around the first turbines. Four 1.5 MW horizontal axis turbines on gravity bases were installed and have been operating since March 2018. The turbines are connected to the power grid at the Ness of Quoys, generating approximately 62 GWh of power as of April 19, 2024.

Stressor-receptor interaction: Changes in benthic habitats and species in the study area along the cable route and at the turbine locations.

Pathway to risk retirement: During consenting, a number of relevant potential impacts were considered as part of the EIA process including direct physical impact and loss of habitat, introduction of new hard structures, and sediment disturbance (MeyGen 2012). Existing site data were reviewed (Scottish Government 2014; JNCC 2024) and, through stakeholder consultation, additional data were requested to determine the presence of benthic habitats and species in the study area. Data collected from a geophysical survey and two benthic surveys showed that no habitat or species of conservation concern were present at the project site and therefore were not likely to be impacted (MeyGen 2012). For extra protection, design features (minimizing the depth and diameter of the turbine foundation piles) and mitigation measures (restricting the area of kelp clearing, including by clearly defining the installation layout) for construction were built into the project (MeyGen 2012). Following the EIA process, consent was granted for Phase 1. A Project Environmental Monitoring Programme (PEMP) was required based on relevant consent conditions (The Electricity Works (Environmental Impact Assessment) (Scotland) Regulations 2000) and was developed by MeyGen with a technical Advisory Group (Rollings et al., 2016a). Benthic habitats along the export cable route and at the turbine locations were also considered during the preparation of the PEMP, but based on the

Figure 6.8. Location of MeyGen Tidal Energy project in Pentland Firth, Scotland (yellow star).

existing and collected data, no benthic habitat monitoring was proposed as no significant impacts were expected from Phase 1A. After consultation with statutory nature conservation bodies (NatureScot, Scottish Environmental Protection Agency), relevant research organizations, and other consultees, the PEMP was accepted by Marine Scotland as the licensing authority (Marine Scotland 2016).

Conclusion: Based on the scale and layout of the project, an examination of existing data from the site, data collected during the surveys, and the advice from the MeyGen Advisory Group, the risk of any significant impacts on benthic habitats was retired for the first stage of the project and no mitigation or monitoring was required during for operation.

Summary of risk retirement:

DEFINE RISK

- Potential risk of impact to benthic habitats and the animals that reside within that habitat.

EXAMINE EXISTING DATA

- Existing benthic habitat data were examined as part of the EIA process.

COLLECT ADDITIONAL DATA

- Benthic seabed surveys were carried out to determine the benthic habitats and species present and the biotope classification. These data were then examined during the EIA, the conclusions of which informed the development of the PEMP.
- Monitoring of benthic habitats and species was not required for the operational stage.

APPLY EXISTING MITIGATION

- No mitigation required during the operational stage.
- Design features and mitigation measures for the construction stage were built into the project to mitigate potential impacts.

MEYGEN TIDAL ENERGY PROJECT – DISPLACEMENT

Contributed by Jennifer Fox and Ian Hutchison (Aquatera Ltd.), and Ian M. Davies (Carronside Consultancy Ltd.)

Project Description: MeyGen is a large-scale commercial tidal array development off the north coast of Scotland (Figure 6.8) with Phase 1 of the project granted planning consent for up to 86 MW (or 61 tidal turbines) (Marine Scotland 2013b). The first stage of the project (Phase 1A) consists of four, 1.5 MW horizontal axis turbines (6 MW installed capacity) on gravity support structures that were installed and have been operating since March 2018.

Stressor-receptor interaction: Displacement of marine mammals, birds, and basking sharks (*Cetorhinus maximus*).

Pathway to risk retirement: Another potential issue identified during the EIA process was effects on marine mammals, birds, and basking sharks from displacement due to the presence of the turbines, physical barriers to movement, displacement due to underwater noise from operational turbines, and indirect effects via changes to prey species (MeyGen 2012). A desktop review of existing data; boat- and shore-based survey data to determine marine mammal distribution, abundance, seasonality, and behavior; ambient noise collected via a towed hydrophone; and benthic survey data were examined (MeyGen 2012). Based on this information, the EIA concluded:

- **Marine mammals** – The impact on marine mammals' ecology is expected to not be significant with implementation of proposed mitigation strategies during construction.
- **Birds** – Due to the relatively small scale of the project and the sensitivity of each species considered to the relevant sources of potential displacement, no significant impacts were identified.
- **Basking sharks** – Due to the relatively small scale of the project and the implementation of mitigation strategies during construction, the impact on basking sharks was considered to not be significant.

Following the EIA process, consent was granted for Phase 1 in 2013 (Marine Scotland 2013b), subject to a PEMP. One element of consideration for the PEMP was displacement of marine mammals, seabirds, and basking sharks during construction and operation. An Advisory Group, made up of representatives from MeyGen, Marine Scotland, NatureScot, and The Crown Estate (now The Crown Estate and Crown Estate Scotland) produced a report to be used for developing the PEMP that concluded "disturbance and displacement impacts (Condition 12 (c)) were low priority for Phase 1[A] and would not be monitored directly. Opportunities with larger turbine arrays could be more relevant and possible in future phases of the project" (Rollings et al. 2016b). Therefore, the risk of displacement was considered retired for the operational stage of Phase 1A (Marine Scotland 2016).

Conclusion: Following the completion of the EIA, consent for Phase 1, and development of the PEMP, the risk of displacement to marine mammals, birds, and basking sharks was retired for operation of Phase 1A with no required monitoring. Mitigation and management measures were required for the construction of Phase 1A.

Summary of risk retirement:

DEFINE RISK

- Risk of displacement to marine mammals, birds, and basking sharks was identified and considered in the EIA.

EXAMINE EXISTING DATA

- A comprehensive desktop review of existing literature was carried out.

COLLECT ADDITIONAL DATA

- Two field surveys were undertaken and baseline underwater acoustic data on marine mammals were collected.
- Monitoring for marine mammals, birds, and basking sharks was not required as part of the operational stage of Phase 1A of the project.

APPLY EXISTING MITIGATION

- No mitigation was required during the operational stage.
- Mitigation and management measures were included during construction of Phase 1A, such as limiting any potential disturbance from vessel activity to seals at haul outs or sensitive areas.

Project Description: Pre-permitted, open ocean wave energy test facility off the coast of Oregon, US (Figure 6.9) with capacity to test up to 20 WECs in four berths and an installed capacity not to exceed 20 MW. Each berth will include WECs, umbilical cables hooked up to subsea connectors, and subsea cables (three conductor alternating current cables, bundled and estimated to have a rated capacity of up to 36 kV) to shore (BOEM 2021; FERC 2021; Oregon State University 2019a).

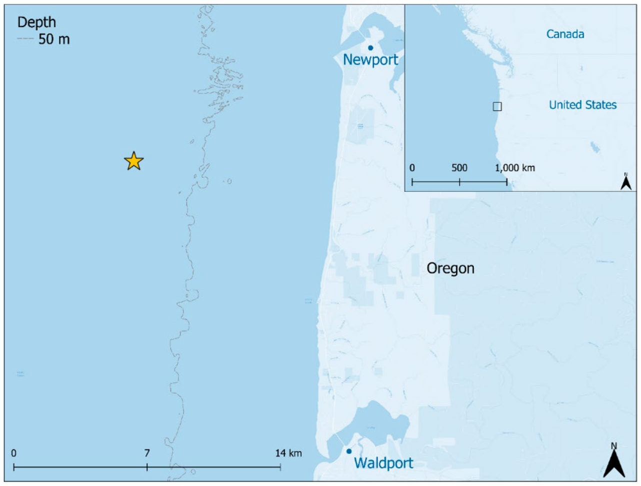


Figure 6.9. Location of the PacWave South test site in Oregon, United States (yellow star).

Stressor-receptor interaction: Impact of EMFs from cables on fish and invertebrates.

Pathway to risk retirement: Research studies and modeling results on EMF emissions were examined to inform concerns on EMFs from cables (Oregon State University 2019b). In particular, a key study commissioned by the Bureau of Ocean Energy Management (BOEM) found no response or biologically significant differences from fish or invertebrates around energized cables and controls (Love et al. 2016) and a summary of the state of the science noted that while species can detect or respond to EMF from subsea cables, EMFs from MRE devices and cables have not been found to negatively impact species, especially for small-scale developments (Gill 2016). These studies informed discussions around potential impacts by the PacWave Collaborative Workgroup, made up of regulatory agencies and other key stakeholders (Freeman et al. 2022).

Although EMF emissions at the site are expected to be low, the power export cables will be buried 1–2 m below the seafloor, or where burial is not possible for the electrical infrastructure (subsea cables, umbilical, subsea connectors, etc.) shielding and armoring will be used to separate sensitive marine species from emissions (Oregon State University 2019b). In addition, a Finding of No Significant Impact determination was made based on the Environmental Assessment for the PacWave South project as a whole (Department of Energy 2021).

Conclusion: Concerns about impacts of EMF from cables were removed based on research studies (Freeman et al. 2022) and the ability to accurately model EMFs (Oregon State University 2019b). Despite finding no significant risk, management measures were applied to limit EMF exposure to the immediate area around cables and other electrical infrastructure (Oregon State University 2019b). An EMF monitoring plan was developed to address uncertainty about EMFs from WECs, which includes modeling EMF emissions, validating these with field measurements from deployed WECs, and reporting exceedances of established thresholds (Oregon State University 2019b, 2019c).

Summary of risk retirement:

DEFINE RISK

- Cables from WECs present a potential risk of EMFs on fish and invertebrates that may be present in the area.

EXAMINE EXISTING DATA

- Key studies (Gill 2016; Love et al. 2016) informed discussions by the PacWave Collaborative Workgroup, which over time diminished concern about EMF effects from cables on marine life.

COLLECT ADDITIONAL DATA

- Not required for risk assessment.

APPLY EXISTING MITIGATION

- Burying or shielding of cables, umbilical, and other electrical infrastructure to minimize EMF exposure. Follow EMF monitoring plan.

MARINE CURRENT TURBINES, SEAGEN – COLLISION RISK

Contributed by Ian Hutchison, Shane Quill, and Jennifer Fox (Aquatera Ltd.)

Project Description: Marine Current Turbines Ltd. (MCT) SeaGen project in the Narrows of Strangford Lough, Northern Ireland (Figure 6.10) consisted of a tidal energy converter with twin 16 m diameter rotors supported on a cross beam that was mounted on a pile-driven monopile, with a total installed capacity of 1.2 MW. The project was consented in 2006, operational starting in 2008, and decommissioned in 2015, with final removal of the structures in 2019.

Stressor-receptor interaction: Risk of collision for harbor porpoise (*Phocoena phocoena*) and local breeding harbor seal population (*Phoca vitulina*).

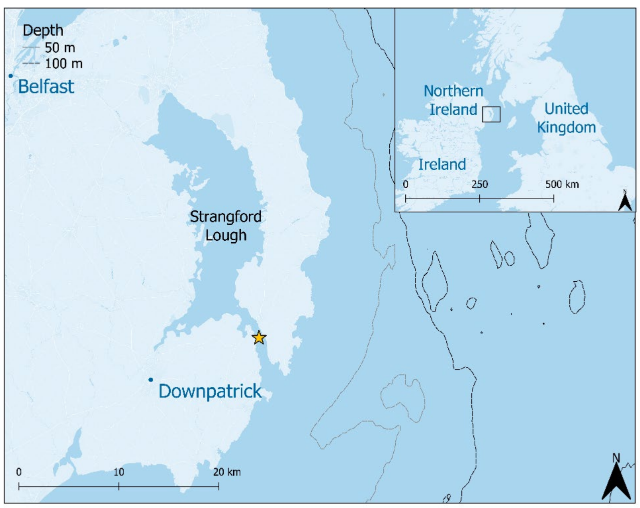


Figure 6.10. Location of the SeaGen project in the Narrows of Strangford Lough, Northern Ireland (yellow star).

Pathway to risk retirement: License conditions required the development of an Environmental Monitoring Programme. Collision risk was identified as a primary concern and a number of mitigation and monitoring measures were prescribed in the Environmental Monitoring Programme (Keenan et al. 2011), including:

- A system of active acoustic monitoring which detected marine mammals within 200 m of the rotors and allowed precautionary shutdown of the turbine;
- Carcass surveys and post-mortem evaluation of all strandings;
- Pile-based, incidental marine mammal observations carried out between July 2008 and August 2009;
- Seal telemetry studies to track individual harbor seals using GPS phone tags;
- Shore-based visual observations of marine mammals in the Narrows around the turbine site; and
- Acoustic monitoring of harbor porpoise activity in the Narrows using passive acoustic monitoring.

Baseline data were collected starting in April 2005 before installation and formed the basis of an Environmental Baseline Report, against which all future monitoring during installation, commissioning, and decommissioning could be compared (Keenan et al. 2011). Post-installation monitoring results were evaluated regularly to assure that any impact of SeaGen on the marine environment could be detected at an early stage. Using an adaptive management approach, the post-installation monitoring data collected provided evidence to support reduction in mitigation requirements (Keenan et al.

2011). In particular, as understanding of the environmental effects of SeaGen grew, the precautionary shutdown distance was gradually reduced from 200 m to 100 m, and eventually to less than 30 m (Savidge et al. 2014). Although the complete removal of the shutdown protocol was authorized, along with fine-scale monitoring around the turbine blades using a new multibeam sonar system, it was not able to be implemented before the device ceased operation in 2015.

Conclusion: The continual analysis of the data collected through the Environmental Monitoring Programme allowed for adaptive management to be applied, and the mitigation requirements around the precautionary shutdown distance to be reduced. While the SeaGen project applied these novel mitigation and monitoring measures, the device ceased operation prior to these being removed and collision risk being retired.

Summary of risk retirement:

DEFINE RISK

- Potential for collision of harbor porpoise and harbor seals with turbine blades causing disturbance, injury, or death.

EXAMINE EXISTING DATA

- An EIA was completed in June 2005 with the production of an Environmental Statement. A number of existing datasets were examined during the EIA.

COLLECT ADDITIONAL DATA

- A baseline marine mammals observation survey was carried out for harbor seals (Davison & Mallows 2005).
- To answer key questions about marine mammals, the Environmental Monitoring Programme included a number of post-installation monitoring measures such as carcass surveys and post-mortem stranding evaluations, marine mammal observations, seal telemetry studies, and acoustic monitoring.

APPLY EXISTING MITIGATION

- No existing mitigation measures required.

TEST NOVEL MITIGATION

- A novel mitigation system was used to detect marine mammals within 200 m of the rotors to trigger precautionary shutdowns of the turbine and reduce collision risk. The requirement was reduced to 100 m, then and 50 m. Removal of the precautionary shutdown was approved, but was not implemented before operation ceased in 2015.

6.2. ADAPTIVE MANAGEMENT

AM is another approach used to aid consenting processes for MRE. AM is an iterative process to decrease uncertainty by conducting environmental monitoring that provides data and information to address specific questions and to inform management decisions on monitoring (Le Lièvre 2020). This approach can aid MRE development by:

- Navigating consenting processes and advancing projects while managing environmental effects with high levels of uncertainty;
- Contributing information to fill knowledge gaps and increase scientific understanding through data collection and learning while doing;
- Aiding evaluation of monitoring and mitigation effectiveness; and
- Providing new information that can lead to risk retirement for stressor-receptor interactions to benefit future MRE developments and support consenting processes (Le Lièvre 2020).

AM may not be well suited to use in situations where the priority is to protect sensitive species, habitats, or resources rather than to address uncertainty, inform development, and enable deployment and adaptability of monitoring requirements, as AM allows for the possibility of failure or potential negative environmental impacts.

Limited guidance is available for applying AM specifically for MRE, though some examples exist. The Welsh government has developed guidance for AM, including for project-level AM and multi-phase projects (Natural Resources Wales 2024). Examples of MRE projects that have used AM approaches are highlighted in Section 6.2.2.

For AM to be effective for MRE, Le Lièvre (2020) provided recommendations which include the need to:

- Develop implementation guidance by responsible government bodies to provide both a common understanding of AM and guide AM plan design for larger-scale MRE projects;
- Produce guidance documents that specify when AM should be used and what elements should be included;
- Identify resources available (time, funds, etc.) and how best to reduce uncertainty via discussions between regulators and developers; and

- Create mechanisms to minimize undue financial risks for developers pursuing an AM approach, while taking into account environmental protection and consistency of applying the precautionary principle.

6.2.1. MANAGEMENT MEASURES

When the priority is protecting the environment and avoiding unacceptable effects, the mitigation hierarchy can be used in conjunction with AM as a precautionary approach to decision-making and development (Elliott et al. 2019; Le Lièvre 2020). If uncertainty, data gaps, or flaws in monitoring design arise during application of an AM approach for MRE projects, the mitigation hierarchy offers options to avoid, minimize, mitigate, and/or restore/compensate for any negative effects with a goal to reduce and mitigate impacts to acceptable levels. However, it should be noted that using such a cautionary approach is likely to hinder the opportunity for learning and reducing uncertainty that is enabled with AM. More information on the mitigation hierarchy can be found in Le Lièvre (2020).

When risks are not well understood, remain uncertain, or a more cautious approach is needed, robust management measures can create greater certainty until data gaps can be filled and an acceptable level of risk is defined, at which time the need for such management measures can be re-evaluated. OES-Environmental created the management measures tool to provide information on management (or mitigation) measures to support the deployment of MRE devices. This tool is available to aid regulators, advisors, developers, and consultants in identifying ways to mitigate possible negative impacts, based on actions that have been used in past or current MRE projects. Management measures that have been used are documented so that each new MRE project need not develop new measures but can learn from others addressing a similar concern. Figure 6.11 shows an example from the tool of a management measure for underwater noise. This tool and the mitigation hierarchy can help projects move forward while managing uncertainty, or until a risk can be retired.

6.2.2. ADAPTIVE MANAGEMENT CASE STUDIES

AM has been used across the MRE industry to help projects move forward in the face of uncertainty, including addressing concerns around scaling up from single devices to larger arrays. Two case studies of AM applications in MRE developments are highlighted below. The following case studies were first presented in Le Lièvre (2020) where more information can be found on each project; this section provides updates on their AM approaches.

ORPC RIVGEN® POWER SYSTEM

The Igiugig Village Council (IVC) has an MRE project in the Kvichak River (Alaska, US; Figure 6.12) where the Ocean Renewable Power Company, Inc. (ORPC) has deployed their RivGen® Power System to provide electricity to the native Village of Igiugig (Igiugig Tribal

Technology	Project Phase	Stressor	Receptor	Management Measure	Advantages	Challenges	Project Documents
Wave, Tidal	Operation & Maintenance	**Underwater noise** The potential effects from underwater noise generated by wave and tidal energy converters.	**Marine Mammals**	**Monitoring** Measure noise generated by device(s) during operation to better understand the potential effects on sensitive species.	Measured noise levels can be correlated with threshold values of relevant species and baseline noise levels of the site to determine impact and need for adaptive management measures.	Can be complex and costly to undertake this type of monitoring in high energy environments. Data and analysis have requirement for acoustic experts.	**SAE Renewables 2011, Aquamarine Power Ltd 2011, Orbital Marine Power 2014, Minesto 2016, Xodus AURORA 2010, European Marine Energy Centre (EMEC) 2019, ScottishPower Renewables 2010, Davison and Mallows 2005, McGrath 2013, Royal Haskoning 2012, Orbital Marine Power 2018, Atlantis Resources Corporation at EMEC, Oyster 800 at EMEC, Minesto Holyhead Deep - Non-grid connected DG500, HS1000 at EMEC, EMEC Billia Croo Grid-Connected Wave Test Site, Sound of Islay Demonstration Tidal Array, Strangford Lough - MCT (SeaGen), Fair Head Tidal Array, Oyster 800 at EMEC, Orbital Marine Power O2 at EMEC**

Figure 6.11. Example of a management measure for underwater noise. The management measures tool offers information on measures used in past or current marine renewable energy projects such as the technology, project phase (installation, operation and maintenance, or decommissioning), stressor and receptor, advantages and challenges, and references to project documents where more information on the measure can be found.

Village Council 2024). The first RivGen® turbine was deployed and tested in 2014 and again in 2015. After securing a Pilot License from the Federal Energy Regulatory Commission (FERC) for a phased approach to deploy two RivGen® turbines (35 kW capacity each) (FERC 2019), the first RivGen® was deployed in 2019 and the second RivGen® was deployed in 2023.

The Kvichak River is home to one of the largest sockeye salmon (*Oncorhynchus nerka*) runs in the world (Fair 2003) and as such, there is a robust fish monitoring plan and resulting AM plan (ORPC 2018). Data collected from underwater video cameras used to monitor fish interaction around an initial turbine deployment in 2015 showed no injuries or behavioral changes to adult salmon during their priority migratory periods (see Chapter 2). These preliminary data provided regulators with confidence to complete the FERC licensing process and pursue an AM approach with the IVC to address remaining fish passage uncertainties specifically associated with the salmon smolt (juvenile) out-migration. The AM Plan that was developed built on ORPC's successful implementation of a similar plan for their Cobscook Bay Tidal Energy Project in Maine, US.

The AM approach and associated monitoring provide data on device interactions with smolt and adult sockeye salmon. In addition, ORPC works with an AM Team made up of regulators and resource managers from federal agencies and Alaska state agencies, as well as technical resource experts from universities and national labs. The AM Team is the mechanism for discussing monitoring requirements based on data collected and findings, and for decision-making, including any changes to the monitoring approach. For example, after undertaking monitoring for several years with no documented collisions and no evidence of impact to adult sockeye salmon, the adult salmon monitoring requirement was removed in 2022 in consultation with the AM Team and in accordance with the annual Alaska Department of Fish and Game Fish Habitat Permit issued for 2022/2023 (Alaska Department of Fish and Game 2022). The risk of project impact to adult salmon has been retired (Alaska Department of Fish and Game 2022). However, the IVC, ORPC, and the AM Team continue to monitor and assess project operations during the smolt out-migration.

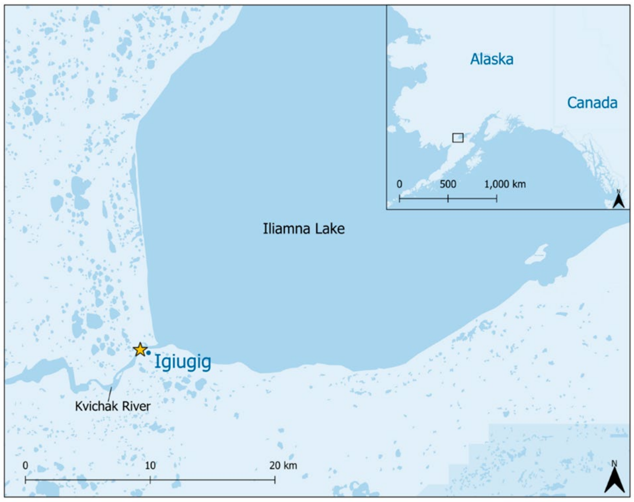


Figure 6.12. Location of the Ocean Renewable Power Company's RivGen® Power System near the native Village of Igiugig in Alaska, United States (yellow star).

The AM approach has allowed the IVC to operate under a FERC Pilot License and demonstrate the project's minimal impact on marine animals and the environment, as well as to deploy ORPC devices while continuing to collect data to further understanding of interactions between smolt and the RivGen® and inform monitoring requirements.

NOVA INNOVATION SHETLAND TIDAL ARRAY

Contributed by Kate Smith (Nova Innovation)

Nova Innovation's Shetland Tidal Array in Bluemull Sound, Scotland (Figure 6.5) was the world's first offshore tidal array to supply electricity to the grid, with the deployment of three Nova Innovation M100 devices (installed capacity of 300 kW) in 2016 and 2017. The next phase involved the installation of one of Nova Innovation's "next-generation" direct drive M100-D turbines in August 2020 followed by two more in January 2023, taking the six-turbine array capacity to 600 kW.

Throughout the lifetime of the Shetland Tidal Array, an AM approach has allowed Nova Innovation to work closely with regulators and stakeholders to continuously review and update monitoring objectives and methodologies, as documented in the PEMP. The first PEMP was approved in 2015, with six further versions issued to date, the most recent being Smith (2024).

Following the award of project licenses for the extended six-turbine array but before developing detailed monitoring methodologies, monitoring principles and objectives were agreed upon between Nova Innovation and Marine Scotland as well as NatureScot and other stakeholders in

2018. This non-statutory step in the process was important to collectively agree on the basis for building the detail of the monitoring program so that it was fit-for-purpose and proportionate. The monitoring objectives were, and continue to be, focused on gathering data to improve understanding for collision risk between tidal turbines and marine wildlife.

Until 2023, land-based bird and mammal surveys had been a part of the PEMP, alongside monitoring of subsea nearfield interactions between marine wildlife and the turbines using turbine-mounted cameras. Starting in 2010, land-based surveys were used to gather data on the presence, abundance, and behavior of marine birds and mammals in Bluemull Sound prior to the installation of any turbines. In March 2020, Marine Scotland approved changes to the methodology proposed by Nova Innovation to narrow the focus of the surveys to gather more detailed information on marine birds and mammals within the array area, following trials of the new methods.

In 2023, Nova Innovation set out the case for ceasing the land-based surveys altogether, based on the following rationale:

1. With the exception of European shag (*Gulosus aristotelis*) and black guillemot (*Cepphus grylle*), marine birds and mammals were consistently recorded infrequently and/or in low numbers in the surveys, indicating very low risk of nearfield encounters with the turbines (Brown 2021; Smith 2022, 2023; Smith et al. 2021).
2. The turbine-mounted cameras used to monitor nearfield subsea interactions between marine wildlife and the turbines have been shown to be highly effective (Smith 2023; Smith et al. 2022).
3. Continuing the land-based surveys would be unlikely to provide any new insights into the nature and frequency of nearfield interactions between marine mammals or diving birds and the turbines or improve understanding for collision risk. To continue with the surveys would be disproportionate to the risk and their benefit.

Marine Scotland, in consultation with NatureScot, approved this request and the surveys ceased in July 2023. This and other changes to the PEMP since 2015 reflect the adaptive nature of the monitoring program, which was adjusted to be proportionate and fit-for-purpose in meeting the specified monitoring objectives.

6.3. MARINE SPATIAL PLANNING

In the marine environment, there are a plethora of existing uses and pressure for new marine sectors, such as MRE, to join an already busy space. MSP is a future-oriented approach that accounts for uses of ocean space, identifies potential overlaps (both conflicts or opportunities for co-existence), and manages a multitude of uses based on policy objectives. The most widely used definition of MSP is a "public process of analyzing and allocating the spatial and temporal distributions of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process" (Ehler 2014; Ehler & Douvere 2009). MSP should be guided by science and be a strategic, iterative, and adaptive process that includes significant participation from marine users and stakeholders (Morf et al. 2019; O'Hagan 2020).

MSP can be used to create a strategic-level guide that provides a vision to help manage different activities that may occur in the same space or time and to achieve policy-level goals (O'Hagan 2020). Strategically, MSP can identify suitable areas for MRE development, particularly ones with low potential for conflicts with existing uses or with high potential for co-use. This includes areas where MRE resources are viable and align with other important factors to consider for MRE (e.g., distance from port/docks, local supply chain, bathymetry, benthic habitat, presence of endangered species, etc.) as well as where conflict with other marine activities and sectors can be reduced (Quero García et al. 2020). MSP can aid MRE on a project level by providing information for consenting processes and assisting with project-scale decision-making, such as siting and helping to facilitate co-location (sharing of space and resources) of marine activities by designating or identifying areas of complementary use (Salvador & Ribeiro 2023). Finding opportunities for co-location based on uses that may overlap and can be integrated based on their use in time and space will become increasingly important; co-location of MRE and offshore wind or MRE and aquaculture are good examples. For example, there is potential for MRE to provide power to aquaculture operations creating low-carbon energy solutions for the aquaculture industry, while the aquaculture industry can provide a stable and commercial demand for the energy produced by MRE (Freeman et al. 2022; LiVecchi et al. 2019).

Several factors have been identified as limiting the use of MSP for MRE, such as lack of clear objectives; knowledge gaps for environmental, economic, social, and political impacts of MRE; data needs to inform MSP development and associated tools to aid implementation; and adequate resources to carry out MSP including financial and human resources (O'Hagan 2020). Other needs include making MSP participatory to actively involve stakeholders in the development process and including practical measures so MSP can streamline consenting. To progress the use of MSP for MRE, it will be important to identify how specific needs for MRE development change based on scale (single devices to arrays) and purpose (small developments for remote or off-grid communities to large-scale arrays for national grid utility power), and assure that these differences are addressed in planning processes. Additionally, incorporating MRE in energy policies and renewable energy goals will create an incentive to plan for and develop MRE, which in turn can help to advance the use of MSP for MRE at a strategic level (Quero García et al. 2020).

Application of MSP is growing worldwide with over 100 countries/territories estimated to have some form of MSP in various stages of implementation; MSP has been increasingly used to achieve sustainable development and growth of blue economies, while considering environmental needs (Intergovernmental Oceanographic Commission 2022; Marine Spatial Planning Global 2022). MSP is employed in several OES-Environmental countries, with a few incorporating MRE into these processes (see online supplementary material). Figure 6.13 provides a summary of OES-Environmental countries and where they are in MSP development.

6.3.1. CASE STUDIES OF MSP FOR MRE

To date, there are few examples of MSP that have helped advance MRE. Several case studies are highlighted below to show how MSP has aided MRE development. As MSP continues to advance in many countries, and more MRE devices are deployed in areas with marine spatial plans, it will be important to continue to share examples and evaluate how MSP affects different maritime sectors, including MRE.

ORKNEY ISLAND MARINE SPATIAL PLAN

Contributed by Shane Quill and Ian Hutchison (Aquatera Ltd.)

Marine Scotland, Orkney Islands Council, and the Highland Council developed the pilot Pentland Firth and Orkney Waters Marine Spatial Plan (Plan) (Marine Scotland & The Highland Council 2016), as an integrated planning policy framework to guide marine development, activities, and management decisions, while also ensuring protection of the marine environment. The Plan is used by the Marine Scotland Licensing Operations Team (MS-LOT) as part of the determination process for marine licensing and consent applications within the Pentland Firth and Orkney Waters. The Highland Council and Orkney Islands Council adopted the pilot Plan as non-statutory planning guidance.

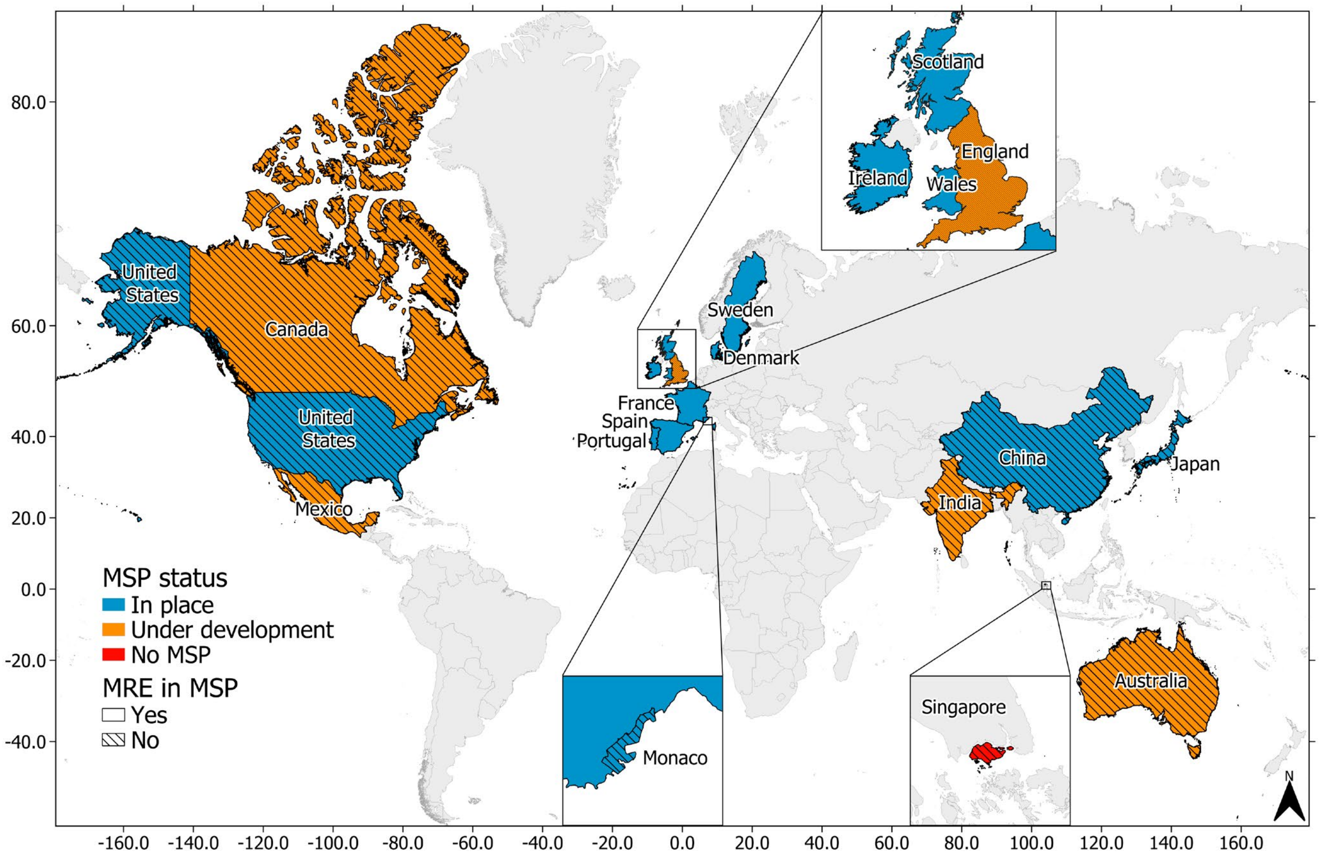


Figure 6.13. Summary of marine spatial planning (MSP) in Ocean Energy Systems (OES)-Environmental countries, with MSP processes specifically including marine renewable energy (MRE). Several countries (e.g., France, England, Mexico, Monaco, United States) only have MSP in place within certain areas, such as regionally or at the state level.

Sustainable growth of the sector and co-existence with other marine users is clearly stated as a key goal within the Plan. The Plan contains several Sectoral Policies that are used to guide development and aid in the determination of license and consent applications. Sectoral Policy 4: Renewable Energy Generation acknowledges that the Pentland Firth and Orkney Waters area has some of the most abundant natural MRE and offshore wind resources in the UK and that the sustainable development of renewable energy projects in the area has the potential to help the UK meet its strategic climate change goals.

The Plan acknowledged that the Pentland Firth and Orkney Waters area was designated as a Marine Energy Park in 2012, within which it was hoped that the commercialization of MRE technologies can be promoted and accelerated. There have been more deployments of MRE technologies in the Pentland Firth and Orkney Waters area than in any other region worldwide, primarily due to the presence of EMEC.

The Plan recognized that knowledge gaps exist for potential environmental effects of MRE projects and that there is a need to undertake environmental monitoring and research to gather relevant evidence to inform the decision-making process. The Plan confirmed support for MRE and offshore wind developments, and encouraged their feasibility in appropriate areas as identified through the Sectoral Marine Plan process. The Plan referred to the existing Regional Locational Guidance and the importance of early and effective engagement with relevant affected stakeholders, as well as avoidance or minimization of adverse impacts or mitigation of any unavoidable adverse impacts.

OREGON TERRITORIAL SEA PLAN

The state of Oregon developed a Territorial Sea Plan in 1994 (Oregon Coastal Management Program 2023). The plan covers a three-nautical mile strip of the coastline in state waters, guides federal and state actions in managing uses and activities of the space, and builds on an earlier Ocean Plan (Oregon Coastal Management Program 1991) to cover the entire 200 nautical miles exclusive economic zone off the Oregon coast (State of Oregon 1994). Developing the Territorial Sea Plan included significant stakeholder engagement activities, geospatial analysis, and environmental considerations to designate areas for siting specific activities while minimizing conflict and adverse impacts.

Beginning in 2009 and updated in 2019, MRE development was included as Part 5 of the plan (State of Oregon 2023). The requirements for siting MRE and offshore wind projects in state waters are described with the goal of protecting ocean resources, ecosystems, and coastal communities. Specific areas are noted in the plan that range from not allowing MRE development (Renewable Energy Exclusion Area) to areas with minimal conflict between resources and uses (Renewable Energy Facility Suitability Study Area) or areas authorized for MRE development testing and research (Renewable Energy Permit Areas).

The Territorial Sea Plan has been used in decision-making for MRE policies (Brandt 2021), for consistency for federal renewable energy projects—for example, as a consideration for development of the cable route for PacWave South (PacWave 2019), and for planning state water components of offshore wind energy lease areas (BOEM 2020).

ZONES TO ENHANCE OR TEST MRE

Designated marine zones and areas prescribed for testing technologies can be considered MSP-adjacent efforts and have been used to advance sectors like MRE. While these exists in several countries around the world, two examples for MRE include Portugal's technological free zones (TFZs) and Australia's Blue Economy Zones (BEZs).

Portugal Technological Free Zones

Contributed by Inês Machado (WavEc)

TFZs are part of a larger government initiative working toward further development of innovation by creating safe spaces (or "sandboxes") that allow testing and experimentation, and encourage the offshore development of renewable technology (Decreto-Lei n.º 67/2021; Portugal Digital 2022). The Decree-Law nº 15/2022 (2022) established the legal framework to implement renewable energy-related TFZs. The primary objective is to promote research, demonstration, and testing of energy-related projects in a real-world environment. TFZs are managed directly by the Directorate General of Energy and Geology, or through concessions awarded by a competitive process.

Portugal's Ordinance 298/2023 (2023) approved a TFZ near Viana do Castelo focused on offshore and nearshore renewable energies to foster innovation and the development of projects for producing electrical energy from MRE and offshore wind energy. This site is located 18 km offshore of Viana do Castelo and is composed of a 7.63 km^2 area designated for pilot projects to test and experiment with wave energy and offshore wind energy technologies. As a part of the Ordinance (Portaria n.º 298/2023), a public consultation process is required with stakeholders.

Australia Blue Economy Zones

Contributed by Irene Penesis and Chris Frid (Blue Economy Cooperative Research Centre)

Funded in part by the Australian Commonwealth government, the Blue Economy Cooperative Research Centre has been exploring implementing BEZs in Australia since 2019. BEZs are offshore (i.e., beyond 3 nm) ocean areas designated for research on emerging blue economy industries, including renewable energy (MRE and offshore wind) and aquaculture, with a focus on sustainability and advancing innovation (Blue Economy Cooperative Research Centre 2022).

To date, one BEZ has been designated in the Bass Strait, between Tasmania and the Australian mainland. Initial environmental and resource assessments have been undertaken, and plans for deployments of aquaculture, MRE, and offshore wind infrastructure trials are advancing. During the planning and development phase of this project, MSP was used to help identify potential areas for the BEZ. A research trial site within the area was selected based on stakeholder input and baseline monitoring data (Blue Economy Cooperative Research Centre 2022).

6.4.
ADDITIONAL TOOLS AND RESOURCES TO AID CONSENTING

There are many additional tools and resources to aid MRE development, some of which are described in this section. Two European Union-funded projects (Wave Energy in Southern Europe [WESE; Portugal and Spain; 2018 – 2021] and Streamlining the Assessment of Environmental Effects of Wave Energy [SAFEWave; France, Ireland, Portugal, and Spain; 2018 – 2024]) have worked toward developing research, resources, and tools to aid consenting and increase understanding on environmental effects of WECs. The first tool developed under WESE is an ecological risk assessment (ERA) framework to identify risks from WECs. Available as an online tool, WEC-ERA, was built for scientists, managers, and decision-makers to use during EIAs for wave energy developments (Galparsoro et al. 2021). The second tool, VAPEM, an environmental assessment and MSP tool, is used to help manage marine activities, incorporate ecosystem services, and identify suitable development opportunities. In addition, the SAFEWave project identified risk-based approaches to aid MRE consenting and developed a risk-based framework (Verling et al. 2023). Verling et al. (2023) identify commonalities and variations between risk-based approaches relevant to MRE, including OES-Environmental's risk retirement process (see Section 6.1) and Scotland's survey-deploy-monitor approach (Marine Scotland 2018; Scottish Government 2023). They use key elements of each to create a risk-based framework for uptake by authorities in implementing consenting processes. The SAFEWave's risk-based framework includes four main steps (Figure 6.14) and notes how other approaches for MRE align with it.

In the UK, several tools have been developed to support MRE consenting. In Wales, Information Notes were developed and written by the Ocean Renewables Joint Industry Programme (ORJIP) Ocean Energy and co-produced with the Welsh Science and Evidence Advisory Group for the Welsh Government to support MRE consenting. The Information Notes provide current understanding of the different environmental effects associated with MRE devices from the perspective of a range of stakeholders including regulators, statutory nature conservation bodies, and industry; identify knowledge gaps; and detail how this is applied to consenting MRE in Wales (ORJIP Ocean Energy 2022b). These technical documents address collision risk, underwater noise, electromagnetic fields, changes in habitat, changes in oceanographic systems, entanglement, environmental monitoring, data transferability, and cumulative impact assessment. In Scotland, Marine Scotland published a consenting and licensing manual for MRE and offshore wind (Marine Scotland 2018). This document provides guidance for those involved in consenting and licensing applications in Scottish waters including energy developers, regulators, advisors, and interested stakeholders.

In the US, the Marine Energy Environmental Toolkit for Permitting and Licensing brings together information on environmental, spatial, regulatory, and scientific information for regulators and developers. The toolkit seeks to increase understanding of environmental effects of MRE projects to reduce assessment timelines and costs for projects, for regulators and developers. This project leverages work from the Pacific Northwest National Laboratory (including OES-Environmental and Tethys), the National Renewable Energy Laboratory, Sandia National Laboratories, and FERC.

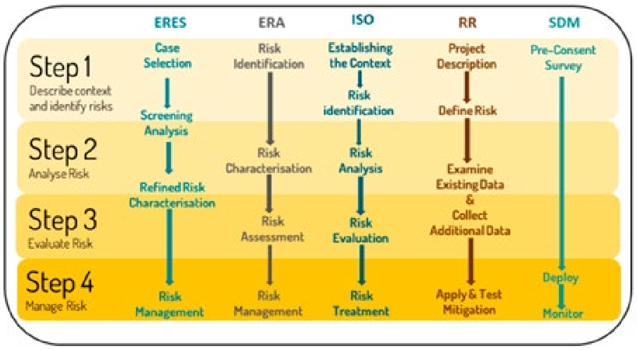


Figure 6.14. SAFEWave's risk-based framework for marine renewable energy (MRE) and other approaches used for MRE, including Ocean Energy Systems (OES)-Environmental's risk retirement (RR) process. ERES = Environmental Risk Evaluation System (Copping et al. 2015); ERA = Environmental Risk Assessment framework; ISO = International Organization for Standardization risk assessment techniques from ISO Standard 31010 (International Electrotechnical Commission, 2019b); and SDM = Survey-Deploy-Monitor guidance. Figure from Verling et al. (2023).

6.5. RECOMMENDATIONS AND CONCLUSION

Risk retirement and data transferability, AM, and MSP are all methods to help the MRE industry progress and responsibly deploy MRE devices, and in turn increase learning and understanding of environmental effects. These approaches can be used individually or in combination with one another and may be used during different stages of MRE development.

Risk retirement and data transferability can be used at all levels and stages of MRE development. At the strategic level, gaining consensus from regulators and advisors on which stressor-receptor interactions can be retired is important. For developers, consultants, and the broader MRE industry, it is particularly important to understand where additional focus is needed for monitoring and mitigation of identified risks, and where coordinated strategic research can be most effective. At the project level, risk retirement can help differentiate between actual risks and uncertainty versus low-risk interactions that can be retired. As part of risk retirement, it is necessary for developers and their consultants to transfer data from other MRE projects, research studies, or analogous industries to inform projects and retire risks, as this will save time and resources. These processes will help ensure that the approach to consenting is proportionate to the level of uncertainty and risk under consideration, and to reduce unnecessary duplication of effort and resources by applying the wider evidence base. Efforts should be made to use risk retirement to lessen financial burdens and move toward proportionate regulatory requirements. To enhance the use and effectiveness of risk retirement throughout the MRE industry, recommendations include the need to develop best management practices for application; to continue sharing examples—both successes and lessons learned; for regulators and advisors to be willing to apply risk retirement and data transferability in consenting processes; to fund and support research on remaining risks not yet ready for retirement; and to carry out additional research as developments increase to larger-scale arrays.

AM has shown to be a useful approach to aid MRE at the project level, particularly in cases where risks cannot be retired or where uncertainty remains, acting as a flexible, learn-by-doing approach to collect data and adapt monitoring over time. AM provides an attractive option for regulators and advisors to consent MRE developments while still allowing for environmental interactions to be understood and action taken, if needed. For MRE developers to be able to incorporate AM approaches, it will be important to identify available resources (time, funding, etc.) and minimize undue financial risks, while balancing environmental protections. To build on successful applications of AM in the MRE industry and continue its use aiding consenting, MRE-specific implementation guidance is recommended that includes a strategic understanding on the best approaches for applying AM to MRE, how to best reduce uncertainty through discussions between regulators and developers during various project stages, and how best to apply AM to larger-scale MRE developments.

MSP is best used during planning and siting stages to identify suitable locations for MRE development within a multi-user space. MSP can aid in strategic-level planning, but to do so, policy- and decision-makers must be aware of the needs for MRE consenting and development to incorporate them into MSP. These needs will vary based on the purpose of an MRE project (grid-connected, providing power at sea, testing, etc.) and can best be incorporated into MSP processes through expert consultation. MSP may also have project-level benefits, particularly if spatial plans can provide guidance, data, and information to aid MRE siting and consenting, as well as reducing conflicts with other ocean users. Where countries or authorities designate specific zones or areas for MRE development, a coordinated approach to environmental surveys and monitoring can be realized, which may lessen the requirements on project developers. To increase the use of MSP for advancing MRE, recommendations include creating incentives for including MRE in energy policies and renewable energy goals, having clear objectives for MRE as part of MSP including incorporating practical measures to streamline consenting, increasing available data and tools to inform MSP development that include MRE needs and fill knowledge gaps (e.g., environmental, economic, social, and political effects of MRE), and identifying future needs for MRE development based on development scale and applications.

These approaches can be key steps in moving beyond challenges and barriers for MRE projects in the face of regulatory and scientific uncertainty, toward pathways for success. As they become more widely used, more MRE devices may be deployed for small- and large-scale developments and commercial projects, providing opportunities to further increase understanding of environmental effects and working to achieve decarbonization and climate goals. By applying these approaches and sharing lessons learned, the MRE industry and regulatory agencies can navigate consenting processes more efficiently and effectively over time. As countries work to achieve their renewable energy goals, using risk retirement and data transferability, AM, and MSP will help responsibly deploy MRE devices in the marine environment and expedite the scaling up and commercialization of the MRE sector.

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Suggested citation:

Freeman, M.C. 2024. Strategies to Aid Consenting Processes for Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 170-203). doi:10.2172/2438595

7.0

Education and Outreach around Environmental Effects of Marine Renewable Energy

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The marine renewable energy (MRE) industry has faced many challenges in getting projects in the water. In many cases, this is due to long consenting timelines, and occasionally active public opposition, often related to concerns about environmental effects or potential conflicts with other uses of the ocean space. While these concerns are very real, some of them are based on misconceptions or lack of familiarity with MRE devices and how they function (Boudet et al. 2020; Karytsas & Theodoropoulou 2014), or uncertainty or misinformation regarding how MRE devices may affect the environment. These misconceptions are common challenges for other renewable energy sectors or other developments in the ocean (Caporale et al. 2020; Scott 2022; Wiersma & Devine-Wright 2014), though the details of device design, site-specific environmental effects, risk and benefit perceptions, and workforce development may be unique to MRE.

Education and outreach about the potential environmental effects of MRE can help policy makers, regulators, advisors, developers, and the public have a better understanding of the realistic level of risk to focus research efforts associated with new projects and maximize the benefits of MRE to local communities while achieving clean energy goals. Often, this requires innovative and diverse methods of communication (in addition to existing forums) and the translation of technical information to common language for relevant audiences (Brooker et al. 2019; Gunn et al. 2022), as well as tailored strategies for reaching each audience (Smith et al. 2022). Building broad awareness of MRE can spark community interest in projects, or increase social acceptance (MacDougall & Colton 2013; Ramachandran et al. 2020, 2021), similar to other global renewable energy projects (Almulhim 2022; Oluoch et al. 2020; Štreimikienė et al. 2022; Zeng et al. 2022; Zografakis et al. 2010). However, it is important to note that no amount of education can completely alleviate individual concerns, because some of the opposition to MRE is based on individual opinion, local cultural values, or place attachment (de Groot & Bailey 2016; Hooper et al. 2020). Instead, these concerns are best addressed and incorporated into each project design through thoughtful stakeholder engagement and trust-building (see Chapter 5).

Another major challenge for the MRE industry is the development of the workforce across environmental and social science research, business, engineering, and technician roles (Constant et al. 2021; Moran 2021). Relevant workforce and skill shortages have affected many marine industries (Burt 2016; Papathanasiou et al. 2018; Safa et al. 2018), and are compounded by competition with other renewable energies. A large range of expertise is needed to design and deploy MRE devices that successfully meet the economic, environmental, and social goals of a location. Targeted, strategic-level education opportunities for science, technology, engineering, and math (STEM) students from primary school to university level, can help increase awareness and build career pathways for students (Maltese et al. 2014; Miloslavich et al. 2022; Pattison & Ramos Montañez 2022). Of key importance is the support of career pathways for traditionally underrepresented people in marine industries, notably, women and people of color (Behl et al. 2021; Johnson et al. 2016; Mackenzie 2015; Scully 2019; Williamson & Wilson 2019). The development of a diverse and inclusive workforce for MRE will foster creativity, facilitate idea sharing, and enable the equitable growth of the industry (Intemann 2009; Sulik et al. 2022).

This chapter discusses how education and outreach can help advance the MRE industry. Past and current efforts are discussed, including examples of successful strategic efforts to increase awareness of MRE and environmental effects, and support of workforce development necessary for industry advancement. The efforts of Ocean Energy Systems (OES)-Environmental on education and outreach regarding environmental effects of MRE are highlighted within this chapter. Project-level outreach is also discussed to recognize how existing MRE projects can provide education and outreach. Last, future needs that build on past and current work to aid the MRE industry are identified.

7.1. EDUCATION AND OUTREACH EFFORTS FOR MRE

Many education and outreach efforts have been initiated to increase awareness of MRE and environmental effects, gain social acceptance, provide education about a specific MRE project, and support increasing the future workforce.

7.1.1. HOW MRE WORKS

Most people are not familiar with MRE, how it works, how or where it can be used, and the possible benefits of the resource. This can create avenues for misinformation or misconceptions, which can increase potentially unnecessary conflict around proposed projects. An important initial piece of education for MRE is offering clear explanations of what MRE is (and what it is not, as compared to offshore wind technology), and how the different technologies operate. Resources have been produced by numerous organizations about this topic for a variety of audiences and age groups. For example, Mystic Aquarium and the National Renewable Energy Laboratory (United States) collaborated to develop an MRE exhibit; the European Marine Energy Center produced a series of animated informational videos that demonstrate how different types of wave and tidal energy devices operate; and the International Renewable Energy Agency has written several technology briefs on MRE. The physics of various wave, tidal, and current energy devices are the most clearly described in available materials, while ocean thermal energy conversion and salinity gradient technologies currently have fewer resources available. This aligns with the focus on each of these technologies in terms of available research as well as technology readiness.

It is also important to provide background on when and why the different types of MRE technologies should be used when other renewable energy technologies are available. Discussing how MRE can help achieve renewable energy goals, be more reliable and predictable than other forms of renewable energy, and how it can often be used where other renewable resources are not available will increase the collective understanding of where and how MRE fits in clean energy transitions. For example, MRE can be used for commercial-scale applications to provide power to the grid, for at-sea uses such as ocean observations and offshore aquaculture or can help support coastal resilience in areas where population centers align with available MRE resources.

7.1.2. ENVIRONMENTAL EFFECTS OF MRE

Providing a baseline understanding of MRE technologies—how they work and where they are best applied—helps pave the way to begin discussing how MRE devices and projects may interact with and potentially affect the environment. An understanding of the site- and device-specific environmental effects of MRE is important for regulators and advisors to appropriately consider potential risk when reviewing and approving projects at both small and large scales of deployment. Access to this information is also necessary for individuals concerned about the impacts of devices on their local ecosystems and communities and is tightly linked to perceptions of social and economic effects (see Chapter 4). Being able to identify which environmental interactions are considered low risk, either from information on existing deployments or transferable industries, and can be retired (see Chapter 6) enables research and monitoring to focus efforts on the remaining uncertain interactions. While education itself does not automatically remove barriers to MRE development, and there are many other factors to consider in stakeholder engagement (see Chapter 5), provision of basic information on environmental effects in a variety of formats can help avoid misconceptions and align public perceptions with the current scientific understanding.

Several projects internationally are working on education around the environmental effects of MRE, including the Offshore Renewables Joint Industry Programme (ORJIP), the Triton project at Pacific Northwest National Laboratory, and OES-Environmental. In this section, the efforts of OES-Environmental are emphasized.

OES-Environmental has focused on sharing current research and existing knowledge to regulators, developers, consultants, researchers, and the public using a variety of learning formats. Creating materials tailored for specific groups has made outreach efforts more effective and allowed the information and findings from OES-Environmental to increase broad awareness about the environmental effects of MRE. OES-Environmental's primary audience for outreach and engagement is the existing international MRE community, which includes regulators, advisors, developers, consultants, and researchers. For regulators and advisors, the focus is on moving from scientific information to application in a regulatory context (Figure 7.1; see Chapter 6 for more information). This has included surveys to understand regulatory perspectives and information needs (Freeman et al. 2020; Rose et al. 2023), workshops to present and discuss available information and the current state of the science, and the development of resources to condense and convert research into formats with specific audiences and applications in mind. For example, a brochure was created to provide an overview of environmental effects particularly for regulators who are new to the MRE industry. In addition, guidance documents were created to aid regulators, advisors, developers, and consultants throughout consenting processes. Several tools have also been developed to aid regulators, advisors, developers, and consultants in finding existing environmental data (Monitoring Datasets Discoverability Matrix) and to provide examples of environmental mitigation from various stages of MRE projects (Management Measures Tool). Webinars have been held to share these resources and tools, answer questions, and receive feedback, in addition to traditional publications and conference presentations. Using surveys and open feedback channels as pathways to learn about audiences and how they perceive content provides insight on effective—or ineffective—education and outreach tactics, as well as helps inform future efforts in this area.

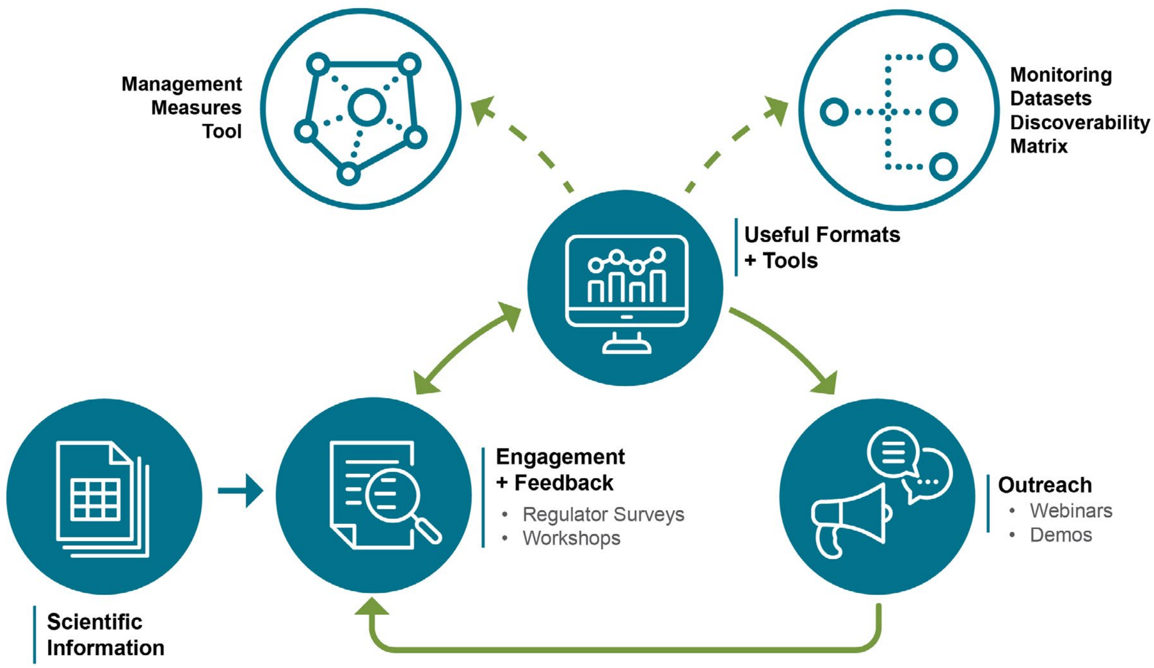


Figure 7.1. Ocean Energy Systems (OES)-Environmental outreach approach for the international marine renewable energy regulatory community—moving from scientific information to application in regulatory processes by creating useful formats and tools for knowledge transfer. See Chapter 6 for additional information on this process. (Illustration by Stephanie King)

OES-Environmental has also explored new formats for sharing scientific information with interested public audiences, including several interview-style podcasts (Figure 7.2) and an article in Sea Technology magazine (Rose et al. 2022). Providing accessible information about the environmental effects of MRE in these formats helps reach new and broader audiences that may not be aware of MRE or environmental effects research, especially because each podcast and magazine has a different but related audience that can be engaged to share information about MRE. Podcasts in particular provide a platform for in-depth, informal 30- to 60-minute conversations about relevant research topics related to MRE that can reach large audiences and can be archived, providing long-term access. This candid approach to sharing research builds trust and transparency and can help reach a wide variety of audiences (Fox et al. 2021), including teachers who have increasingly used podcasts as a tool for lesson enhancement (Gopal et al. 2020). Similarly, magazine articles are transitioning to digital platforms, making the content more sustainable and accessible, and easy to share and link to relevant content channels.

For all audiences, OES-Environmental also uses social media and the Tethys platform to host and promote events and content. Social media enables communication to audiences within the MRE community. However, it can also help reach those outside the research community using nontechnical, nonscientific language in a timely way that can help increase transparency and gain trust from specific audience groups, as well as challenge misconceptions and misinformation (Fox et al. 2021; Huber et al. 2019; Weingart & Guenther 2016). Additionally, social media channels can serve as opportunities to promote research and information about renewable energies (Zobeidi et al. 2022), especially for audiences and communities who might not traditionally have access to scientific information (Dosek 2021; Mueller-Herbst et al. 2020).

Social media handles (@Tethys_Enviro on X, Instagram, and Facebook) are shared between several projects and regularly post about information from OES-Environmental on environmental effects of MRE as well as information from other projects on MRE and wind energy. OES-Environmental also promotes events and content through bi-weekly Tethys Blasts, a newsletter curated for the marine and wind energy communities. Both these social media and newsletters help increase the availability of information for different audiences.

Development of STEM educational material for students and the future MRE workforce around environmental effects is another growing piece of OES-Environmental's outreach work (Freeman et al. 2023). Various types

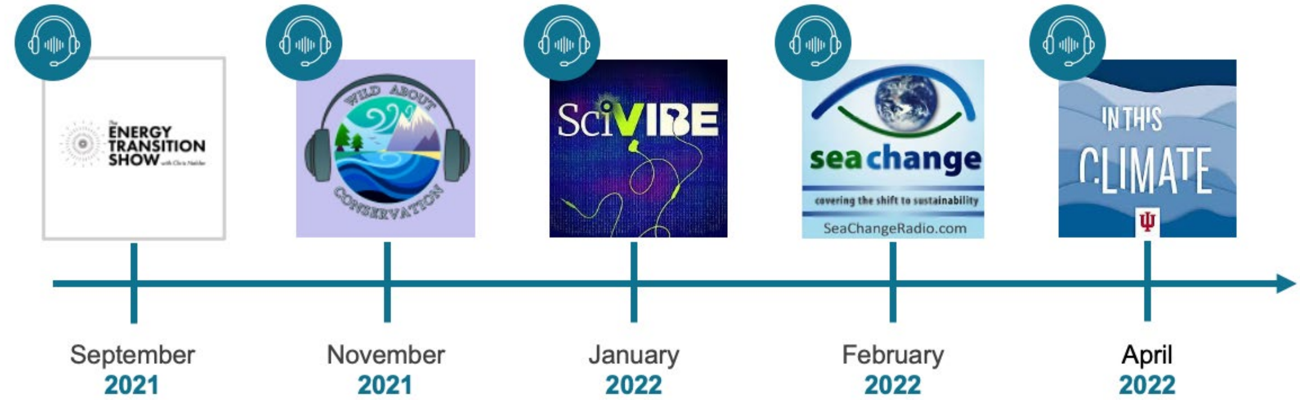


Figure 7.2. Podcast episodes in which Ocean Energy Systems (OES)-Environmental staff have been interviewed. Links to the podcasts can be found on Tethys. (Illustration by Stephanie King)

of content have been developed and are hosted on the Tethys MRE Educational Resources page with STEM students in mind, ranging from primary school to university students (Figure 7.3), though have been found to be useful for other interested audiences as well.

As OES-Environmental continues to synthesize current scientific knowledge about the environmental effects of MRE, strategic outreach and engagement will continue to be a focus to assure important findings are communicated in accessible ways to diverse audiences.

7.1.3. WORKFORCE DEVELOPMENT

To spur innovation and promote growth in MRE, the industry needs to inspire the next generation of MRE workers. There is also growing interest in supporting people working in other energy sectors, the supply chain, or other maritime sectors to transition into the MRE sector. The International Energy Agency (IEA)-OES International Vision for Ocean Energy projected that 300 GW of MRE could be deployed and 680,000 direct jobs could be created globally by 2050 (Huckerby et al. 2016). The MRE industry will need a workforce that mixes strong ocean construction, nautical design, and ocean science with an understanding of advanced materials, innovative power system development, and control theory. Additionally, the industry needs to recruit scientists to perform environmental, social, and economic evaluations of MRE technologies and projects and influence policy to reduce deployment and commercialization barriers. Project support on the business, management, regulatory, legal, and financial side of the industry may also need MRE-specific knowledge. Despite increasing interest in MRE, the beginning stages of the industry present workforce pipeline challenges, including a lack of experience and awareness of potential careers, and competition from other industries for workers.

Efforts to address these needs include more programs and improved program accessibility at all education levels in addition to an increased awareness of MRE as a renewable energy career (Constant et al. 2021).

Figure 7.3. Examples of educational content developed or supported by Ocean Energy Systems (OES)-Environmental with science, technology, engineering, and math students in mind. Links to more can be found on Tethys. (Illustration by Stephanie King)

There is much work to be done, but at a minimum, the following must be increased to strengthen the global workforce pipeline:

- Relevant work experiences in MRE or adjacent fields,
- Industry engagement in academia,
- Hands-on learning, and
- MRE-specific coursework for all grade levels.

Many countries have developed workforce training programs or initiatives to navigate some of these challenges and aid in the development of the MRE workforce. Examples of a variety of international workforce development efforts are listed in Section 7.1.5.

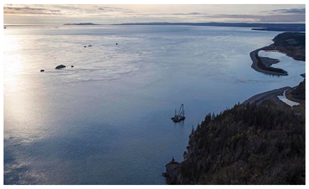
7.1.4. PROJECT-LEVEL OUTREACH

A significant component of MRE project development includes outreach and engagement with stakeholders and others who may be interested in or affected by a new project. While strategic engagement is important to broaden the understanding of MRE, reduce potential concerns or barriers to its deployment, and build the workforce, MRE projects have a unique opportunity to conduct outreach and provide education to local communities and specific stakeholders that may not be reached with general efforts. Stakeholder engagement and participatory planning for MRE are covered in more detail in Chapter 5, though these efforts centered around projects often include information sharing or development of educational content. The combination of project-specific efforts and strategic- or government-level efforts to build public awareness and develop a skilled workforce is needed to advance the industry in particular locations and as a whole (Constant et al. 2021; Freeman 2020).

Several MRE projects or test centers have developed educational outreach materials, as shown in Figure 7.4.

7.1.5. ADDITIONAL EDUCATIONAL OR WORKFORCE TRAINING RESOURCES FOR MRE

The list in Table 7.1 provides examples of resources for MRE that have been developed by many different organizations internationally. While the list is by no means exhaustive, the hope is that by collating and sharing these resources further collaboration can be fostered, and more viewers will be able to access the resources.



Fundy Ocean Research Centre for Energy (FORCE), a tidal energy test site in Canada, operates a visitor center that is free and open to the public both in-person and virtually, and an online learning portal that provides real-time data, an animated tour of the test site, and education information on tidal energy.

European Marine Energy Centre (EMEC), a wave and tidal energy test site in the United Kingdom, developed a Marine Renewable Energy Dive-In Pack, a suite of engaging educational resources for primary school children.

Biscay Marine Energy Platform (BiMEP), a wave and offshore wind energy test site in Spain offers a virtual tour with educational videos of the open water BiMEP site and test installations and the breakwater-integrated Mutriku site.

Pacific Marine Energy Center (PMEC), a marine energy research collaboration with University of Washington, Oregon State University, and University of Alaska Fairbanks in the United States offers a variety of STEM opportunities in higher education, and K-12, such as a wave energy coloring book.

Figure 7.4. Examples of outreach efforts internationally. Fundy Ocean Research Centre for Energy (FORCE); European Marine Energy Centre (EMEC); Biscay Marine Energy Platform (BiMEP); Pacific Marine Energy Center (PMEC). STEM = Science, Technology, Engineering, and Math

Table 7.1. Compilation of educational or workforce training resources for marine renewable energy (MRE). Updated list available on Tethys.

	Blue Economy Cooperative Research Centre	The Blue Economy Cooperative Research Centre in Australia is an innovative cross-sectoral research collaboration that hosts an Education and Training Program for researchers to deliver industry-ready PhD graduates.
	COME3T	Committee of Experts for Offshore Renewable Energies Environmental and Socio-economic Issues (COME3T) is a committee of experts in France that provides scientific knowledge and develops helpful visual information in multiple educational bulletins. COME3T is coordinated by France Énergies Marines.
	Deftiq Offshore Renewable Energy Courses	Deftiq, in partnership with multiple academic and industry organizations globally, has produced online MRE and offshore wind courses for technology developers, early career researchers, and other workforce development. Multiple courses have been developed, including a course on environmental impact.
	FLORES	Forward Looking at the Offshore Renewables (FLORES) is a large-scale partnership aiming to advance offshore workforce development across the European Union.
	FloWave	The FloWave Ocean Energy Research Facility offers multiple opportunities for teachers to visit the test facility and participate in competitions.
	INORE	The International Network on Offshore Renewable Energy (INORE) is an association of postgraduate students, postdoctoral researchers, and other professionals at early stages of their careers, working in the fields of offshore wind, wave, tidal, salinity gradient, and ocean thermal energy conversion.
	Integral Consulting CStories	Integral Consulting developed a MRE chatbot that uses artificial intelligence to answer any question about MRE.
	Marine Energy Collegiate Competition	The U.S. Department of Energy hosts a challenge for interdisciplinary teams of undergraduate and graduate students to advance MRE by exploring opportunities for MRE technologies to benefit other existing maritime industries via real-world concept development experiences.
	Marine Energy Wales School Resources	Marine Energy Wales has developed online education resources that are available in English and Welsh, for primary and secondary school students.
	MATES	The Maritime Alliance for fostering the European blue economy through a Marine Technology Skilling Strategy (MATES) project aims to increase ocean literacy with emphasis on offshore renewable energy and shipbuilding, as well as to raise awareness about maritime careers. Eleven pilot experiences in training and skills development have been created and are freely available on the MATES website.
	MRE Brochure	The MRE brochure was developed by Ocean Energy Systems (OES)-Environmental to provide an overview of the environmental effects of MRE development, to familiarize readers with the latest scientific information on the potential impacts of installation and operation of MRE devices in a condensed, visual format.

	NEED Project Curriculum	The National Energy Education Development (NEED) curriculum provides comprehensive, objective information and activities for students and educators on the energy sources that can power the United States, including economic and environmental impact information.
	ORJIP Ocean Energy	Offshore Renewables Joint Industry Programme (ORJIP) Ocean Energy is a United Kingdom-wide collaborative program of environmental research with the aim of reducing consenting risks for wave, tidal and current projects.
	POES Network	The Pan American Ocean Energy Student (POES) Network, created by the Pan American Marine Energy Conference (PAMEC) Energy Association and Centro Mexicano de Innovación en Energía (CEMIE)-Océano, is a student and early career research-led organization for those in the Americas involved in the MRE sector.
	PRIMRE STEM Page	The U.S. Department of Energy's Portal and Repository for Information on Marine Renewable Energy (PRIMRE) hosts a STEM (sciences, technology, engineering, and mathematics) page to support the workforce development in the MRE industry.
	REDi Island	Renewable Energy Discovery (REDi) Island is an interactive, educational 3D animation of a virtual renewable energy-powered island developed by the National Renewable Energy Laboratory in the United States. that—with help from the next generation of waterpower scientists—could soon become reality.
	SafeWAVE Project	The SafeWAVE Project, a multidisciplinary team from Portugal, Spain, France, and Ireland, has developed an education and public engagement framework to enhance ocean literacy, and as part of this work reviewed existing education and public engagement programs.
	Spark Squad comic book	The Spark Squad comic book, developed by the National Renewable Energy Laboratory, follows secondary students as they learn about waterpower technologies, including MRE.
	Tethys Engineering Photo Library	The Tethys Engineering Photo Library hosts photos and illustrations of MRE devices, arrays, and facilities that are available for use. The Photo Library can be a useful resource for showing existing MRE technologies designs to increase awareness and familiarity.
	Triton Newsletter	The Triton Initiative at Pacific Northwest National Laboratory carries out research and environmental monitoring technologies to reduce barriers to testing, and sharing the information broadly. The Triton newsletter is used to facilitate this information dissemination.
	Water Power STEM to Workforce	The Water Power STEM to Workforce project focuses on assessing the workforce needs in the United States and supporting the development of educational structures to build the marine pipeline.
	WEAMEC	The West Atlantic Marine Energy Community (WEAMEC) is a consortium of 30 institutions across France that has developed a training roadmap and various initial and continuing training programs for marine energy technical skills.

7.2.
FUTURE NEEDS AND CONCLUSION

As the MRE industry continues to progress internationally, education and outreach needs will evolve as well. Consistent education and outreach at both the project- and strategic-levels are essential to increase and maintain public awareness, grow the knowledge base around the environmental effects of MRE technologies, and generate further interest in joining the MRE workforce and supporting project developments. To do this effectively, plans for communicating and disseminating information about MRE should be embedded in the research process to assure education and outreach efforts are accurate, current, and appropriately messaged to keep audiences properly informed. Outreach efforts should be creative, with content developed for specific and diverse audiences (Freeman et al. 2023), and paired with best practices for scientific communication (Gunn et al. 2022) and evaluation of effectiveness (National Academies of Sciences, Engineering, and Medicine 2017; Rodgers et al. 2020). Further workforce development will need to be undertaken with an eye to leveraging resources and lessons learned internationally and from the offshore wind industry, where applicable, as standardization and training programs are developed and connected to more mature marine industry workforce pipelines (Constant et al. 2021).

For OES-Environmental, going beyond scientific publications, reports, and conference presentations enables a further reach with project outcomes, allows for crafting messages for specific audiences in an evolving public space, and employs a range of techniques and formats to deliver similar messages to evaluate and increase effectiveness. In future work, continued and improved collaboration and cross-promotion of materials with like-minded initiatives and organizations internationally is recommended to develop synergies and better leverage existing networks and content.

7.3.
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Suggested citation:

Rose, D. J. 2024. Educational and Outreach around Environmental Effects of Marine Renewable Energy. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 204-216). doi:10.2172/2438596


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8.0

Marine Renewable Energy Data and Information Systems

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As the marine renewable energy (MRE) sector grows, large amounts of environmental and technical data and information are being collected. When these data and information are openly available, they can be used to guide research and development, inform responsible siting and consenting of projects, and increase stakeholder understanding through transparency. For example, quality environmental data collected during the siting, consenting, construction, operation, and decommissioning of MRE projects can all play key roles in better characterizing baseline conditions, developing effective monitoring and mitigation strategies, and retiring environmental risks through data transferability (see Chapter 6). Ensuring that these data and information are easily discoverable and accessible will help the MRE sector make informed decisions and coexist in an increasingly busy ocean environment.

Data and information systems, such as data repositories, data portals, and geospatial data platforms, play key roles in data management, stewardship, and use. Some systems host raw and/or derived data products, while others may include analyzed and interpreted information, data processing features, modeling and software tools, visualizations, mapping interfaces, and/or educational content. This chapter highlights several of the data and information systems focused specifically on MRE research, development, and deployment around the world, as well as other marine and environmental data systems that may be applicable to the MRE sector.

8.1. MRE DATA AND INFORMATION SYSTEMS AROUND THE WORLD

Several national and international data and information systems host and disseminate data and information relevant to MRE development in a variety of formats.

8.1.1. INTERNATIONAL SYSTEMS

The Portal and Repository for Information on Marine Renewable Energy (PRIMRE) is the centralized system for MRE data, information, and resources in the United States, much of which is relevant to the international MRE community. PRIMRE is primarily made up of seven knowledge hubs (Figure 8.1), each with its own unique structure and purpose: the Marine and Hydrokinetic Data Repository (MHKDR) hosts datasets, Tethys hosts environmental documents, Tethys Engineering hosts technical documents, the Marine Energy Projects Database hosts information on deployment activities, Marine Energy Software hosts relevant software, the Marine Energy Atlas hosts geospatial data, and Telesto hosts development guidance. PRIMRE also hosts a variety of additional tools and resources intended to support the international MRE community, including an events calendar, educational content, archived webinars, a free-use photo library, and an online newsletter. Finally, PRIMRE links to international MRE data systems to encourage data sharing for universal and transparent access around the world.

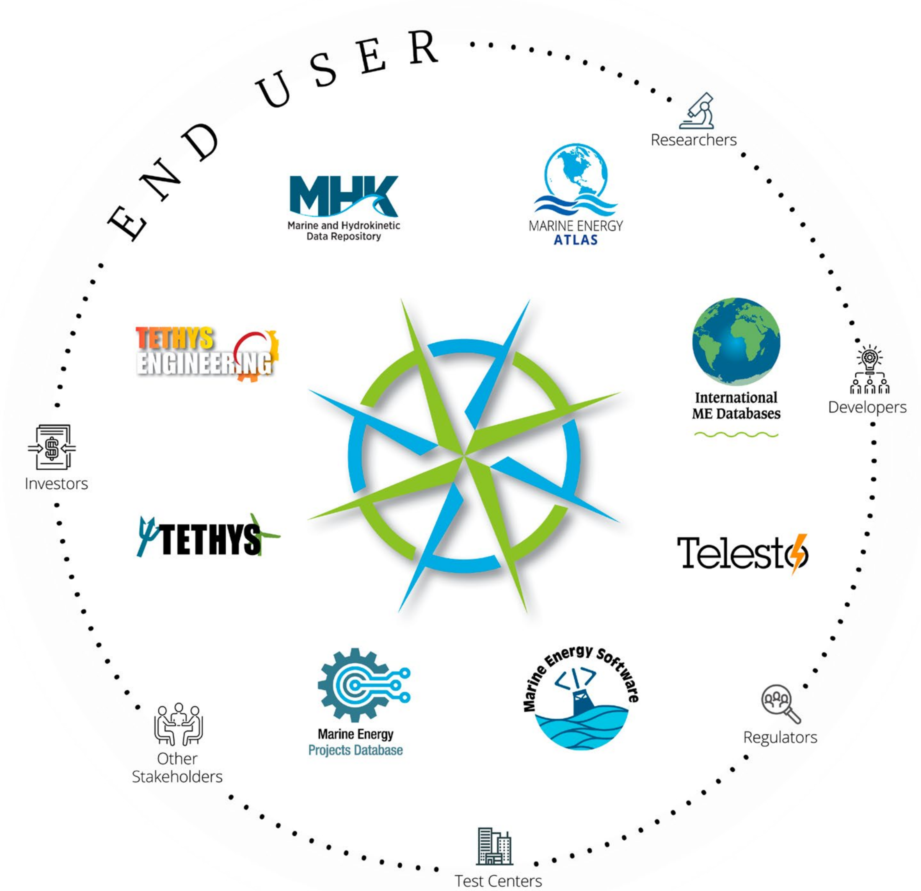


Figure 8.1. Graphic depicting the Portal and Repository for Information on Marine Renewable Energy (PRIMRE), its knowledge hubs, and their relation to relevant user groups.

Within PRIMRE, information and resources about the environmental effects of MRE development are hosted on Tethys (Figure 8.2). The Tethys Knowledge Base is a comprehensive collection of documents, including journal articles, scientific reports, and conference papers, that cover a range of environmental topics, such as underwater noise effects on marine mammals and fish collision risk with tidal turbines. The documents can be easily filtered, searched, and sorted, to provide an understanding of different areas of MRE research. Another key feature is the Tethys Blast online newsletter, which provides bi-weekly updates on new publications in Tethys, upcoming events, funding and employment opportunities, and international news relevant to the MRE sector.

Tethys also serves as a collaborative space and dissemination platform for the Ocean Energy Systems (OES)-Environmental initiative (see Chapter 1)—a collaboration among 16 countries dedicated to studying the environmental effects of MRE development around the world. To improve understanding and support efficient project consenting, OES-Environmental synthesizes available data and information and develops publications, online tools, and other resources for different stakeholder groups. For example, OES-Environmental has published a series of Guidance Documents that can be used to evaluate the environmental, social, and economic effects of MRE within a general regulatory context (see Chapter 6). Tethys also features a variety of educational resources that can be used by students of all ages and educational backgrounds, including coloring pages, animated videos, and an interactive video game: Marine Energy Adventure: Collision Risk (see Chapter 7).

OES-Environmental also collects information, or metadata, about many of the activities around the world that are examining the potential environmental effects of MRE devices through monitoring or research. Each Marine Energy Metadata page provides detailed information about the MRE project or research study, including its scope, methods, and results, as well as links to available publications and monitoring reports. The metadata forms were used to examine environmental effects activities around the world (see Chapter 2). Similarly, the Monitoring Datasets Discoverability Matrix is an interactive tool that allows regulators, developers, and the larger MRE community to easily discover datasets from already consented projects that can be used to aid consenting processes for future MRE projects. By making this information widely available, OES-Environmental aims to enhance transparency around environmental monitoring efforts to advance the global state of knowledge and the industry in an environmentally responsible manner.

Figure 8.2. Graphic depicting Tethys, an online knowledge hub with information and resources on the environmental effects of marine renewable energy and wind energy globally. Tethys is one of seven PRIMRE (Portal and Repository for Information on Marine Renewable Energy) knowledge hubs.

Another key international MRE data system is MAREN-DATA, a dedicated data platform that hosts environmental monitoring and resource characterization data collected through the Streamlining of Ocean Wave Farms Impact Assessment (SOWFIA), Strategic Environmental Assessment of Wave energy technologies (SEA Wave), Wave Energy in Southern Europe (WESE) projects, and Streamlining the Assessment of Potential Effects of Wave Energy (SafeWAVE). The platform features datasets from many of the major MRE test sites throughout Europe, including the Biscay Marine Energy Platform (BiMEP) in Spain and the European Marine Energy Centre (EMEC) in Scotland. Available data from the test sites include underwater noise data and video capturing seabed ecology and species behavior.

The European Biofouling Database, developed as part of the OCEANIC project, provides data and information about challenging biofouling species throughout Europe, including non-native species associated with MRE and related marine equipment. The database provides data and information on the occurrence of fouling species and key biofouling parameters, such as thickness and weight, to support the MRE industry in understanding the biofouling communities their devices are more susceptible to at a given site and to facilitate informed decision-making (Vinagre et al. 2020).

8.1.2. NATIONAL SYSTEMS

AUSTRALIA

The Australian Marine Energy Atlas, hosted on NationalMap, provides interactive maps of Australia's wave and tidal energy resources and additional information on supporting infrastructure and spatial constraints in the marine domain, such as ports and shipping routes, fisheries and aquaculture, and marine and coastal parks. Building on prior assessments, the Atlas compiles outputs from several projects, including the Australian Wave Energy Atlas Project and the Australian Tidal Energy (AUSTEn) project.

CANADA

The Marine Energy Resources Atlas Canada is a web-based geospatial data application developed by National Research Council Canada to assist MRE stakeholders with preliminary site selection and feasibility investigations in the rivers and coastal waters in western Canada. The Atlas can investigate scenarios with different resource, socio-economic, and environmental criteria and support decision-making for MRE.

FRANCE

The French Resource Center for Offshore Renewable Energy (RESCORE) is an online platform that provides access to information relevant to the offshore renewable energy sector in France, including environmental and physical data, reports, and recommendations. The platform initially focused on the results derived from France Énergies Marines' research and development projects but is gradually taking in data from other MRE stakeholders and projects, including DTOceanPlus.

RESOURCECODE is a marine data toolbox with modeling and software tools that enable resource characterization and allow wave and tidal technology developers and supply chain companies to improve designs and optimize operations. The toolbox uses laboratory data, existing models, satellites, and the extensive MetOcean datasets held by test sites, creating the highest resolution wave model in North West Europe.

IRELAND

Ocean Energy Ireland provides access to marine data, maps, tools, funding, and information relevant to MRE site assessment, development, and management in Ireland. The platform hosts a comprehensive inventory of environmental, social, and economic data relevant to all offshore renewable energy developments in Irish waters, including data from the Atlantic Marine Energy Test Site and Galway Bay Test Site.

UNITED KINGDOM

In the United Kingdom (UK), Marine Data Exchange stores, manages, and disseminates marine industry data from across England, Wales, Northern Ireland, and Scotland, including all the offshore survey data that seabed lessees and other stakeholders are required to submit to The Crown Estate and Crown Estate Scotland. The platform hosts environmental, social, and physical data from a variety of industries, including MRE, offshore wind, and subsea cables, as well as data from research projects.

The UK Atlas of Marine Renewable Energy is a free online geographic information system (GIS) interface that provides publicly available data about waves, tides, and winds in UK waters. Unique exploration tools are available to complement the resource maps and enable a greater understanding at site selection.

8.2.
OTHER RELEVANT DATA AND INFORMATION SYSTEMS AROUND THE WORLD

In addition to the MRE sector-specific data and information systems detailed in the previous section, there are many regional, national, and international systems focused more generally on marine data that may also be relevant to MRE development and better understanding of its environmental effects.

8.2.1.
INTERNATIONAL SYSTEMS

The European Marine Observation and Data Network (EMODnet) is a network of organizations that provides access to European marine data across seven discipline-based themes, including biology, human activities, and seabed habitats. All data is freely available, and the European Atlas of the Seas displays numerous data layers provided by the EMODnet thematic portals.

Copernicus Marine Service, part of the European Union's Copernicus Programme, aims to boost the blue economy across all maritime sectors by providing free data and information about the state of the oceans on a global and regional scale. The Copernicus Marine Data Store offers different types of marine data, information, and services, ranging from oceanographic data to educational content.

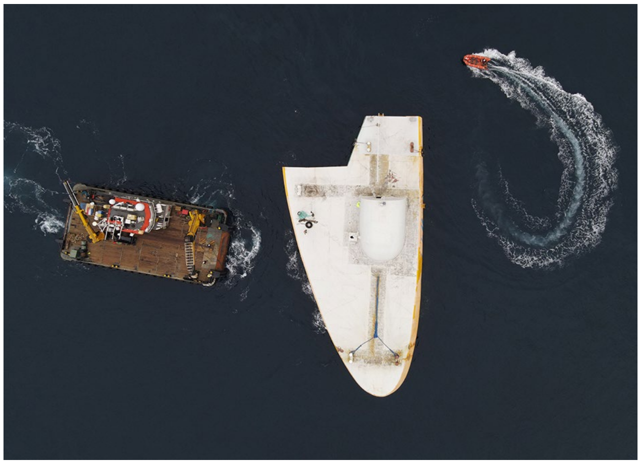
8.2.2.
NATIONAL SYSTEMS

CANADA

The Canada Marine Planning Atlas is an interactive mapping tool for decision-makers and other users to access and discover geospatial data layers relevant to ecological processes, bioregion features, and human activities in Canada's marine spatial planning areas. The Atlas is supported by Fisheries and Oceans Canada and divided into the Atlantic Atlas and Pacific Atlas.

FRANCE

GéoLittoral disseminates information and geographical data on maritime spatial planning and the marine and coastal environments in France. Géolittoral's planning portal maps data are produced as part of the implementation of public policies supported by French ministries, including MRE data.



Milieu Marin France facilitates the sharing and dissemination of public data and information on the marine environment using a centralized system that pulls from multiple national and regional portals. Its Marine Environment Information System (SIMM) provides data related to sustainable development in the marine environment.

Sextant is another geographic data system that documents and disseminates a catalogue of data related to the marine environment in France, including key regulations, habitats, and species. The geographical data present on Sextant stems from research projects at the French Research Institute for Exploitation of the Sea (IFREMER) and its partner laboratories.

IRELAND

The Integrated Mapping for the Sustainable Development of Ireland's Marine Resource (INFOMAR), Ireland's national seabed mapping program, delivers freely available, high-resolution seabed imagery derived from multibeam echosounder data in the Irish Exclusive Economic Zone. The INFOMAR Marine Data Download Portal provides bathymetry, backscatter, and sub-bottom data.

UNITED KINGDOM

The Marine Environmental Data and Information Network (MEDIN) aims to improve access to and management of UK marine environmental data and information. MEDIN delivers data through a network of accredited Data Archive Centers, accessible via the MEDIN Portal. MEDIN also provides metadata standards and established data guidelines to assist with consistent data collection and archiving across the UK.

Marine Scotland's National Marine Plan Interactive (NMPi) is an online tool and data portal that enables access to spatial information relating to marine environment and activities in Scotland. Developed to support national and regional marine planning, the interactive tool builds upon Scotland's Marine Atlas.

UNITED STATES

The National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Information (NCEI) provides access to global coastal, oceanographic, geophysical, climate, and historical weather data in a variety of formats. NCEI develops software, application programming interfaces (APIs), visualization methods, and other services to enhance data access, discovery, and interoperability.

Supported by NOAA and the Bureau of Ocean Energy Management, Marine Cadastre works with national, regional, and state partners to develop and provide direct access to the best available data and tools to meet the growing needs of the blue economy. Data are shared in real time with partners, including regional ocean data portals and other data sharing platforms, and regulatory agencies for use when siting MRE deployments.

8.3. RECOMMENDATIONS

There are several regional, national, and international systems that store, organize, and disseminate the data and information needed to advance MRE development in an environmentally responsible manner. Many of the governments and organizations behind these systems are making concerted efforts to assure that their data and information are high quality and FAIR—findable, accessible, interoperable, and reusable—in accordance with the FAIR principles for scientific data management and stewardship (Wilkinson et al. 2016).

Whenever possible, environmental data should be made openly available to be freely used, re-used, and shared by anyone for any purpose. If data cannot be made openly available, clear metadata should be made available to the public to promote their discovery and provide owners' contact information. Open data can hold immense value, particularly for newly developing sectors like MRE, so enabling efficient and effective data sharing should also be a priority for everyone from data managers and researchers to regulators and industry. The development and adoption of international data standards could further support the collection and sharing of high quality and comparable data around the world. When MRE data and information are openly available and easily discoverable by all audiences, they can be used to innovate within the MRE sector, inform other ocean uses, and help answer environmental research questions of interest to the broader scientific community.

Ensuring the longevity of data and information gathered within the MRE sector is also paramount for reducing duplication, sustaining progress, and fostering collaborative advancements. Since project financing has a finite duration, the preservation of data is critical. It is likely that key environmental datasets have already been lost, each of which could have helped address priority gaps and uncertainties. Establishing long-lasting data sharing initiatives is not only a commitment to transparency but also a strategic investment in the collective knowledge base of the international MRE community.

8.4. REFERENCES

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Suggested citation:

Farr, H. 2024. Marine Renewable Energy Data and Information Systems. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 218-224). doi:10.2172/2438597

Section E

BEYOND STRESSOR-RECEPTOR INTERACTIONS


NOVA

9.0

Beyond Single Marine Renewable Energy Devices: A System-wide Effects Approach

Authors: Lenaïg G. Hemery, Daniel J. Hasselman, Marie Le Marchand, Georges Safi, Elizabeth A. Fulton, Andrea E. Copping

Global expansion of renewable energy, including marine renewable energy (MRE) technology development is necessary to mitigate the effects of climate change, facilitate a sustainable transition from carbon-based energy sources, and satisfy national energy security needs using locally produced electricity (European Commission 2022; IPCC 2023; IRENA 2020). As MRE engineering and research continue to focus on designing devices for deployment in nearshore and offshore waters around the world, researchers are also examining potential environmental effects on marine animals, habitats, and ecosystem processes. To date, the focus has been on interactions between small numbers of MRE devices (1–6) and the environment, such as collisions between animals and turbine blades, the effects of underwater noise and electromagnetic field (EMF) emissions, changes in habitats and oceanographic processes, risk of entanglement of animals, and displacement of animals (Boehlert & Gill 2010; Copping & Hemery 2020) (see Chapter 3).

Most of the knowledge of environmental effects has focused on potential outcomes of single (or a few) operational devices, especially in temperate areas. As MRE arrays and larger projects develop in the coming years, it is vital to understand how our knowledge of potential environmental effects might increase in scale, how they may translate to changes in ecosystems, and how they may interact with ongoing and future uses of the oceans. Potential effects of an expanding MRE industry must be placed within the context of other offshore developments. Through international collaborations, Ocean Energy Systems (OES)-Environmental is expanding its view of potential environmental and ecological effects of MRE development to include a broader look at higher level, system-wide effects. This broader perspective consists of investigating how to 1) increase the understanding of environmental effects of MRE from single devices to arrays, 2) apply an ecosystem approach to the integrated management of MRE, and 3) assess the cumulative effects of MRE with other anthropogenic activities at sea.

Future large-scale commercial MRE arrays will be in operation for decades. It is crucial to increase our understanding of environmental effects on marine animals and habitats to comprehend the full effect of this new low carbon energy generation and help facilitate sector growth, aid the transition of energy systems to renewable sources, and address the effects of climate change. Although our knowledge about stressor-receptor interactions for single devices and small arrays continues to improve (Copping & Hemery 2020), remaining uncertainties complicate the task of predicting how marine animals and habitats will interact with, and be affected by, large-scale arrays (Onoufriou et al. 2021). Research and monitoring around small deployments have provided substantial information to better understand the potential environmental effects of large-scale arrays. These effects are unlikely to scale linearly with the number of devices (Zhang et al. 2022), but rather in complex and nuanced ways. For this topic, OES-Environmental has examined how to apply the knowledge of stressor-receptor interactions from single devices to arrays. It also required exploring interactions that are not significant around single devices but that may become important around large-scale arrays, such as changes in oceanographic systems or displacement of animals around MRE developments.

To evaluate the potential effects of MRE development on the broader marine ecosystem, OES-Environmental has assessed the application of an ecosystem approach as defined by the international Convention on Biological Diversity, which currently does not address MRE. The approach follows an integrated strategy to manage land, water, and living resources while equitably promoting conservation and sustainable use. Scientific methods are applied to characterize the fundamental processes, functions, and interactions among organisms and their environment. While the ecosystem approach is a complex concept that integrates environmental, economic, and social sciences, OES-Environmental has initially focused on the environmental aspects of the approach. This topic used conceptual frameworks to explore how MRE development and operation may affect local ecosystems and associated food webs, and to describe how ecosystem services may be influenced by MRE. The development of such frameworks aids qualitative and quantitative descriptions of the interactions between ecosystem components (both biotic and abiotic) and MRE systems.

Cumulative environmental effects result from interacting activities across space and/or through time in one location, due to sequential or overlapping anthropogenic activities. The most complicated cumulative effects arise from combinations of both direct and indirect effects of the many activities that occur within a region over time. As MRE development approaches the state of commercial-scale deployment, projects will be installed in areas where other anthropogenic activities already exist, and environmental interactions between activities are likely. The understanding of environmental effects of MRE has matured to a point where there is sufficient information to begin assessing the potential cumulative effects of MRE development, even though many knowledge gaps remain. With this topic, OES-Environmental investigated how to define the cumulative effects of MRE developments, how these effects combine with or affect those of other human uses of marine environments, and the tools and research studies that can be used to best assess these effects.

Projections of potential future effects and the state of the environment into which MRE will be developed will assist planners, funders of projects, and decision-makers in determining their feasibility, smoothing the way for large-scale array deployment. By taking this system-wide effects integrated perspective, OES-Environmental lays out a pathway to expand the understanding of the environmental and ecological effects of MRE development across the appropriate spatial and temporal scales, based on existing research, leveraging information on MRE devices, and highlighting gaps in scientific knowledge. The following sections also identify the main knowledge gaps, limitations, and future research needs. In addition, they each lay out a robust scientific approach for testing hypotheses that can be applied to increase understanding of the environmental effects of MRE development at greater spatial, temporal, and technological scales.

9.1. 'SCALING UP' OUR UNDERSTANDING OF ENVIRONMENTAL EFFECTS OF MRE DEVELOPMENT FROM SINGLE DEVICES TO LARGE-SCALE COMMERCIAL ARRAYS

This section is a summary of a study published as a journal article (Hasselman et al. 2023) in which the authors adapted and applied cumulative environmental-effects terminology to the stressor-receptor interaction approach, in order to conceptualize how effects may scale up with large-scale MRE arrays.

9.1.1. THE NEED TO UNDERSTAND HOW ENVIRONMENTAL EFFECTS SCALE UP

A variety of obstacles impede the global expansion of the MRE sector, including difficulties in obtaining regulatory approvals required for project development due to uncertainty about environmental effects. Despite our growing understanding of the effects of various stressor-receptor interactions for single devices and small pre-commercial arrays, predicting the potential effects of large-scale commercial arrays on marine animals, habitats, and ecosystems is made more difficult by the uncertainties that still exist (Copping et al. 2016; Copping & Hemery 2020).

As stated above, it is unlikely that environmental effects will scale linearly with the number of operational devices deployed (Copping et al. 2016; Zhang et al. 2022). Environmental effects of large-scale arrays are anticipated to be site-specific, nuanced, contingent on array configuration, cumulative, and may exhibit non-linear environmental responses. Therefore, Hasselman et al. (2023) established generalized concepts about how effects for key stressor-receptor interactions might manifest with the development of large-scale arrays. These generalized concepts provide a basis for the development and testing of hypotheses that will help enhance predictions and comprehension of potential risks associated with expanding MRE deployments to large-scale commercial arrays. Consequently, the development of these generalized concepts informs MRE project siting and reduces barriers to project consenting by providing a robust scientific approach for developing and testing hypotheses that can be applied to increase our knowledge of the effects of arrays. This information is crucial for understanding potential risks of MRE expansion and developing effective mitigation strategies (as required). It is also needed to facilitate the development of MRE projects at scales that can make meaningful contributions to addressing the impacts of climate change, ensuring a sustainable transition of global energy sources, and safeguarding energy security.

9.1.2. APPROACH APPLIED TO INVESTIGATE THE SCALING-UP OF ENVIRONMENTAL EFFECTS OF MRE

Hasselman et al. (2023) developed and applied a structured approach (i.e., a multi-step framework) for conceptualizing how environmental effects might scale up to arrays for seven key stressor-receptor interactions (i.e., collision risk, underwater noise, EMFs, changes in habitats, changes in oceanographic systems, entanglement, and displacement). The framework included: i) a description of the interaction, ii) a summary of existing knowledge about the interaction based on available literature and relevant information from surrogate industries, iii) defining how effects of the interaction might manifest for arrays and identifying any caveats that need to be considered that could influence this perception, and iv) identifying the type(s) of research required to improve our understanding of the effects of the interaction for large-scale commercial arrays (Figure 9.1). Much of the information available about stressor-receptor interactions from single MRE device deployments and from surrogate industries was suitable for assessing how environmental effects might scale up and facilitated the implementation of this structured approach.

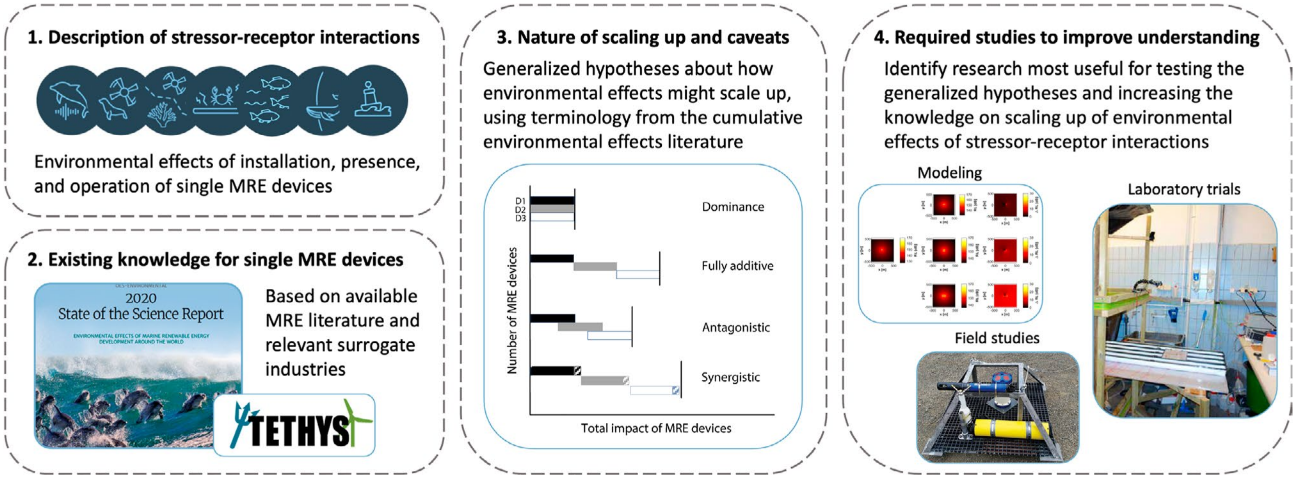

Figure 9.1. Summary of the four-step framework developed for assessing how the environmental effects from seven stressor-receptor interactions may scale up from single marine renewable energy (MRE) devices to arrays. (From Hasselman et al. 2023)

Generalized concepts for how the effects of stressor-receptor interactions might scale up (i.e., step 3 of the framework) were developed using terminology adapted from the cumulative environmental effects literature, providing an informative framework for developing this nomenclature. While the field of cumulative environmental effects typically focuses on describing the nature of interactions between different stressors (e.g., habitat loss, invasive species, climate change, etc.) (Carrier-Belleau et al. 2021; Halpern et al. 2008a), Hasselman et al. (2023) were concerned with understanding how the effects of the same stressor-receptor interaction might change with an increasing number of MRE devices. This required adaptation of existing terminology to reflect comparatively simple additive or more complex non-linear (e.g., multiplicative) effects, and generated four broad classification categories (i.e., dominance, additive, antagonistic, and synergistic effects):

- Dominance effects describe a scenario where the effect of one MRE device overwhelms the effect of other devices in an array.
- Additive effects describe a scenario where the effects of each MRE device add up to those of the other devices in an array. In other words, it reflects the sum of effects for each device in an array.
- Antagonistic effects describe a scenario where the effects do not fully add up but somewhat partially cancel each other out. The sum of effects for each device in an array is scaled to reflect a diminished effect as the number of devices increases.
- Synergistic effects describe a scenario where the combined effect of all devices in the array is greater than the sum of their individual effects. It arises from a scalar applied to each device's individual effects resulting from the interactions among each other.

9.1.3. APPLICATION OF THE SCALING-UP FRAMEWORK TO THE MRE CONTEXT

Hasselman et al. (2023) generated a series of hypotheses for how environmental effects from seven key stressor-receptor interactions may scale up with the development of large-scale commercial arrays (Table 9.1).

Current knowledge about the environmental effects of stressor-receptor interactions from single MRE devices is relevant and important for developing hypotheses about the potential effects of arrays. For instance, knowledge about how underwater sound propagates over space generated the expectation that the effects of underwater noise would scale in an additive manner with an increasing number of operational devices. This, in turn, led to the hypothesis that the area over which noise would be higher than baseline levels would increase commensurate with array size, but that elevation in received levels would increase in a non-linear fashion. Conversely, comparatively little information is currently available about the environmental effects of some other stressor-receptor interactions (i.e., displacement, entanglement, changes in oceanographic systems) because an unknown threshold number of operational devices is required before such effects can manifest and become detectable. As such, this work highlights the value of existing post-installation programs for collecting environmental effects data for

Table 9.1. Summary of hypotheses for how environmental effects from stressor-receptor interactions may scale up with large-scale marine renewable energy (MRE) commercial arrays. (Modified from Hasselman et al., 2023)

Stressor-receptor Interactions	Environmental Effects: Dominance	Additive	Antagonistic	Synergistic	Notes
Collision risk		×	×	×	Dependent on array layout, configuration (e.g., 'in parallel' vs. 'in series'), MRE technology type, site location, and species' ability to detect devices and avoid/evade collisions
Underwater noise		×		×	Area over which sound will be elevated will increase with array size; elevation in received levels will increase non-linearly
Electromagnetic fields	×	×	×		Electromagnetic fields increase linearly with additional electrical current; effects may be influenced by spatial arrangement of subsea cables
Changes in habitats		×	×	×	Complex effects that may vary across spatiotemporal scales, with array geometry, and equivalency of effects for individual devices within an array
Changes in oceanographic systems		×	×	×	Effects observed at some threshold number of devices; dependent on MRE technology, number of devices, array configuration, and site-specific hydrodynamics
Entanglement		×	×		Risk increases with number of MRE devices, but dependent on scale and configuration of mooring lines/cables, depth at MRE site, and animal behavior/movement
Displacement		×		×	Effects observed at some threshold number of devices; no single threshold applicable across species or MRE technology type

facilitating MRE expansion, such as adaptive management (Le Lièvre 2020), but sets realistic expectations for understanding the effects of some stressor-receptor interactions until more operational MRE devices are deployed.

Results from this work suggest that while the environmental effects for some stressor-receptor interactions may scale up in a predictive manner (i.e., additive effects for underwater noise), the effects for some other interactions (e.g., collision risk, changes in habitats, etc.) may be influenced by a variety of compounding factors that need to be considered (e.g., environmental heterogeneity, physical habitat characteristics, biological constituents of the environment, spatial arrangement of an array, etc.). Consequently, these factors may generate a variety of context-specific expressions for environmental effects (i.e., dominance, additive, antagonistic, or synergistic effects) as the number of devices in an array increases and is based on the arrangement of devices in an array. This highlights the inherent complexity of understanding environmental effects and suggests that effects observed for an array in one location may not necessarily be indicative of the effects of an array in a different area. The further development of standardized methodologies for assessing environmental effects of arrays will be important for determining the extent to which the various factors influence the effects of arrays.

Finally, Hasselman et al. (2023) identified a suite of research efforts that are required to help fill knowledge gaps, several of which could be undertaken in the near term, in order to improve our understanding of environmental effects for single MRE devices and large-scale commercial arrays. For some interactions (e.g., EMFs), improved knowledge about effects first requires the development of sufficiently robust sensors to collect in situ measurements around operational devices, followed by systematic measurements over a range of power outputs from operational devices. For others (e.g., changes in habitats), a deeper understanding of effects requires the consistent collection of high-quality baseline habitat data using standardized approaches prior to device deployments. A recurrent theme across several stressor-receptor interactions (i.e., collision risk, displacement, entanglement, changes in oceanographic systems) was the need for numerical simulations and new, or improved, modeling approaches to advance our understanding of effects, which are supported by empirical data collected using standardized and appropriate methods to validate (or refute) model predictions. Importantly, future modeling endeavors ought to take into account practical array configurations that are restricted by the physical constraints of the environment, such as geography, water depth, hydrodynamic complexities, bathymetric constraints, etc., as opposed to the theoretical configurations used most commonly to model and optimize energy extraction efficiency (e.g., Bryden et al. 2007; Turnock et al. 2011).

9.1.4. CONTRIBUTION TO UNDERSTANDING SYSTEM-WIDE EFFECTS

Hasselman et al. (2023) outlined an approach and provided guidance to improve our ability to differentiate between unknown and actual risks of MRE development, identify critical knowledge gaps, and facilitate the global expansion of the MRE sector in the near term. The generalized concepts established in this study provide a basis for developing testable hypotheses so that a robust scientific approach can be used to improve our understanding of the effects of large-scale commercial MRE arrays. Importantly, this study identifies how various factors (e.g., environmental heterogeneity, physical habitat characteristics, array configuration, etc.) could influence how effects from different stressor-receptor interactions manifest. In addition, it cautions against the indiscriminate application of monitoring results across differing marine ecosystems without an appropriate level of empirical data collection using standardized methodologies to validate assumptions and confirm expectations.

While much of the work outlined above can be undertaken in the near term to improve our understanding of the potential effects of arrays, it is crucial to remember that ecosystem components and stressors do not exist in isolation, and as the MRE sector grows, relationships between stressor-receptor interactions may amplify impacts at wider spatiotemporal scales (see below). Research on this subject may become important in the future and could be conducted alongside efforts to understand ecosystem-level effects and cumulative environmental impacts of MRE development (see Sections 9.2 and 9.3).

9.2. HOW CAN ECOSYSTEM APPROACHES SUPPORT INTEGRATED MANAGEMENT OF MRE?

This section is a summary of a study in preparation (Le Marchand et al. pers. comm.) in which the authors assessed the application of the ecosystem approach to the MRE context, especially by leveraging the lessons learned from its application to other marine sectors.

9.2.1. THE NEED FOR AN ECOSYSTEM APPROACH

The coastal ecosystems into which MRE is developed are already subject to numerous pressures such as climate change, fisheries, extraction of raw materials, maritime transport, tourism activities, contamination, and underwater noise from diverse sources. Marine ecosystems are based on complex networks, linking biological components and environmental parameters in a dynamic balance. Any additional pressure from the installation and operation of MRE devices can therefore have direct effects on one or more components of the ecosystem, and indirect effects on other, related components. However, the current approach of investigating environmental effects of MRE looks at effects of each stressor-receptor interaction on individual species and in isolation, even though species are parts of an ecosystem and linked by food web interactions.

The ecosystem approach is a technique for environmental management that incorporates both natural and human-made components into the biotic and abiotic aspects of ecosystems within a comprehensive framework, founded on an all-encompassing understanding of how ecosystems function (Borja et al. 2016). With the use of the ecosystem approach, stakeholders can thoroughly evaluate a range of choices for the sustainable development of MRE technologies, taking into account their effects on the environment and any potential ecosystem-level ramifications (Hammer 2023). Supporting a systematic understanding of ecosystem-level effects and coordinated management of marine environments is an ongoing challenge. Using both qualitative and quantitative data, integrated approaches provide relevance to the causal linkages between complex ecological and socioeconomic processes that support the coexistence of societies and ecosystems (Isaksson et al. 2023).

To support an integrated management of MRE development worldwide and minimize impacts on ecosystem processes, an ecosystem approach must be applied to: (1) identify any resulting disruptions to ecosystem functioning and services; (2) quantify and contextualize the magnitude of any such disruptions; (3) track the efficiency of management responses; and (4) model changes to the structure and function of the ecological processes.

9.2.2. APPROACHES AVAILABLE FOR APPLYING AN ECOSYSTEM APPROACH TO THE MRE CONTEXT

Le Marchand et al. (pers. comm.) reviewed the ecosystem approach numerical tools that are commonly implemented in various marine studies and assessed how they might be applied to the MRE context. Understanding community structure, species composition, and ecological roles on a qualitative and quantitative level is necessary for managing marine ecosystems. The increasing reliance of operational and strategic planning on quantitative models is driving society's goal of predicting how the ocean will respond to disruptions. However, such methods can be prohibitively resource intensive, or inconclusive when available data is poor. Qualitative models can provide a rigorous alternative. According to Dambacher et al. (2003), qualitative models offer an unweighted perspective on the direct and indirect impacts that may result from the addition of pressures such as MRE devices.

The ecosystem approach extensively relies on ecosystem models that can be used to address a wide range of issues and situations. They can be employed to characterize ecosystems and their complexity, consider interspecific interactions, define indicators, and contribute to the implementation of management plans by decision-makers. These models can be data-intensive due to their quantitative structure and the size and complexity of some ecosystems; each model has its own scope, emphasis, data needs, mathematical foundations, and ecological assumptions. The most promising numerical modeling techniques in the MRE context are listed below.

Minimum Realistic Models are limited to elements of an ecosystem that significantly interact with the species or activity being studied. In the MRE context, these models might be helpful in places where species of particular concern are expected to be impacted by MRE devices. The Models of Intermediate Complexity for Ecosystem assessments (MICE) consider the dynamics of key components of ecosystems and the factors influencing them, and have been primarily used in fisheries and river management (Plagányi et al. 2014). Bayesian models are based on conditional probabilities and a network of nodes that represent the cause and effect relationships within a system, and are mostly used in the context of energy-generating technologies, fisheries, conservation, and offshore wind energy (Adedipe et al. 2020; Trifonova et al. 2021).

Size-Based Models explore the role of size structure in marine ecological processes. These modeling approaches have been most frequently used to examine the effects of fisheries and climate change on pelagic ecosystems. Because of their efficiency, they can also be applied to questions around MRE development. Mizer is a dynamic multispecies size-spectrum model that tracks individual sizes and uses individual physiological rates and predation preferences to infer population-level dynamics (Woodworth-Jefcoats et al. 2019). Mizer is computationally efficient and easy to implement, but not inherently spatial. In contrast, the Object-oriented Simulator of Marine ecOSystem Exploitation (OSMOSE) is a multispecies individual-based model, which assumes opportunistic predation based on size adequacy and spatio-temporal co-occurrence between a predator and its prey (Halouani et al. 2016). Both models have been used to explore fisheries and climate change questions and could easily be extended to MRE.

Trophic-Based Models represent the food web in an ecosystem, from low trophic levels (e.g., phytoplankton) to top predators. These models may help address a variety of potential MRE impacts, such as artificial reef or reserve effects, since they are based on the interaction between prey and predator and include intricate representations of environmental dependencies and impact-response functions. Ecopath with Ecosim (EwE) use spatial-temporal dynamic simulations to study the energy transfer throughout the food web (Christensen & Walters 2004). The interface can dynamically depict human causes of disturbance as well as environmental forces. EwE is largely used in fisheries, climate change, offshore wind energy, and coastal development (Serpetti et al. 2021). An alternative approach, Linear Inverse Models (LIM), calculates the flow of the food web from empirical data using inverse modeling. This approach is most often used to model questions related to plankton communities (van Oevelen et al. 2010).

End-to-End Models provide a holistic representation of the ecosystem, integrating both biological compartments (low and high trophic levels) and physical processes, as well as anthropogenic aspects, which could make them relatively straightforward for application to the MRE context. Atlantis includes physical environmental drivers and biogeochemical processes spanning food web- and habitat-mediated interactions, as well as human uses of marine and coastal areas and their management arrangements (Pethybridge et al. 2020). StrathE2E2 is an ecological mass-conserving dynamic model coupled with a fishing fleet model (Thorpe et al. 2022). Both models are employed for fisheries- and climate change-related issues, as well as conservation and coastal development topics.

In addition to models, the ecosystem approach often employs indicators to express effects and changes in ecosystem structure and functioning in terms of management measures that can address them (Trifonova & Scott 2024). The indicators should ideally match the characteristics or services of the ecosystem in which stakeholders and policymakers are interested. A suite of indicators spanning various data, ecosystem components, and processes is ideal, as no single indicator can fully capture the dynamics of an ecosystem. Some examples of such indicators are listed below.

Species- or functional group-based indicators that pertain to the biomass, production, or consumption ratios of species, as well as the species and functional group composition. Stakeholders may easily comprehend these types of indicators, but users must be mindful of how specific an indicator is to the activity of interest, as some are sensitive to various environmental stressors. In the MRE context, potential species-oriented indicators may be used to evaluate the artificial reef effect of devices and associated infrastructures (Raoux et al. 2018).

Size-based indicators, that are traditionally used in a fishery context, correspond to changes in the structure of fish communities. These indicators, such as the Large Fish indicator and the Typical Length indicator, may be useful to evaluate whether the prohibition or restriction of fishing operations inside MRE arrays has created a potential reserve effect, similar to that of a marine protected area, consequently increasing the size of the targeted organisms (Roach et al. 2018). However, signals in size-based indicators may take a long period of time to become evident, based on the growth rate of the target species.

Functional indicators relate to the functioning of the ecosystem and food web, and the role of species within the ecosystem. Trophic-level based indicators are at the interface between structural and functional indicators. Both indicators inform the role played by individual species (or groups) considering their trophic level and biomass (Pauly 1998). These indicators could be pertinent to MRE, where species at different trophic levels may be affected differently.

Ecological network analysis indices are designed to integrate the intricacies, dynamics, and natural fluctuations of the ecosystem while examining interactions to discover and describe emergent characteristics. While they are more difficult for stakeholders to comprehend than structural indicators due to their complexity, they offer in-depth information on ecosystem dynamics and the impacts of ecological drivers. In addition, they are among the few indicators to consider ecosystem structure and functioning (Safi et al. 2019).

9.2.3. APPLICATION OF THE ECOSYSTEM APPROACH TO THE MRE CONTEXT

Although few studies to date have applied an ecosystem approach to MRE development (e.g., Alexander et al. 2016), the approach has been employed in the context of other anthropogenic marine activities (e.g., offshore wind, fisheries management) in ways that may be transferable to MRE. The ecosystem approach may provide answers to certain environmental questions that have been raised with the development of MRE.

The main effects that may occur as a result of MRE development on the behavior of megafauna (i.e., marine mammals, diving seabirds, elasmobranchs, fishes, and large invertebrates) are due to underwater noise and EMF emissions, as well as the risk of collision with moving parts of turbines. These effects can vary greatly among trophic groups, MRE technologies, and project sites. Each of these effects could lead to avoidance of an MRE development area by numerous individuals of multiple species from various trophic levels, ultimately resulting in a trophic cascade for the impacted ecosystem. Even though changes in animals' behavior related to various stressor-receptor interactions may be limited and more research is required, the impacts of a trophic cascade could have lasting consequences on ecosystem structure and function (Ripple et al. 2016). Integrating such intricate and dynamic changes into ecosystem approach models remains a challenge.

Submerged structures can create an artificial reef effect that may boost local species richness and attract a variety of animals, such as detritus feeders, benthic predators that come to feed on biofouling, and organisms that seek shelter in these habitats, such as juvenile fish aggregating on and around structures. The artificial reef effect can improve biomass and species richness while also enhancing the amount of organic matter in the ecosystem (Sheehan et al. 2020). Because of this income of new species and increase in biomass, fish aggregation around MRE infrastructure and the artificial reef effect may, directly or indirectly, cause a trophic cascade in ecosystem structure that is mediated by feeding interactions (Figure 9.2). Such changes in habitats caused by MRE devices could lead to changes in the structure and functioning of the entire food web within the area of an MRE array. Applying the ecosystem approach through an ecosystem model such as OSMOSE or EwE enables the inclusion of a diverse set of species or functional groups to assess their trophic interactions (Raoux et al. 2017).

When other human activities are completely or partially prohibited close to MRE devices as a safety precaution, a reserve effect may occur. Restricting access to the region and reducing fishing pressure can increase the biomasses of fish, crustaceans, and mollusks (Alexander et al. 2016). This may, in turn, lead to a spillover effect (Figure 9.2). Fisheries populations that have been overfished may be able to recover because of biomass increases facilitated by MRE infrastructure. The fishing industry has raised questions regarding the reserve effect and resulting potential for spillover. Consequently, it has been the subject of numerous ecosystem approach studies, using EwE models within the context of both MRE arrays and offshore wind farms (Alexander et al. 2016; Halouani et al. 2020).

Large-scale development of MRE arrays may influence physical oceanographic processes that control an ecosystem, like waves, tides, currents, temperature, or salinity (Whiting et al. 2023). For example, a change in turbulence could lead to changes in community patterns for fish, benthic invertebrates, and macroalgae (du Feu et al. 2019). However, site-specific differences are likely, and it may be challenging to generalize and extrapolate across locations. Biogeochemical models provide a connection between the ecosystem dynamics of lower trophic levels (e.g., phytoplankton and zooplankton) and marine biogeochemistry (e.g., water quality, nutrients) (van der Molen et al. 2016). Such models could be implemented with more realistic array sizes and configurations to consider the effects of changes in oceanographic systems around MRE arrays on lower trophic levels and their productivity. Additionally, physical-biogeochemical models could be coupled to trophic models in end-to-end modeling within the ecosystem approach to explore questions related to oceanographic changes due to the presence and operation of MRE arrays.

Lessons learned from applications of the ecosystem approach to other anthropogenic marine activities can be applied to assessing the potential ecosystem-wide effects of MRE development. For example, trophic interactions in an ecosystem modeling framework would be appropriate to study the potential MRE-related effects on predators as these interactions demonstrate how targeted species may respond to varying degrees of pressure (Kiyota et al. 2020). As such, models used in the fishery approach, such as OSMOSE, Mizer, EwE,

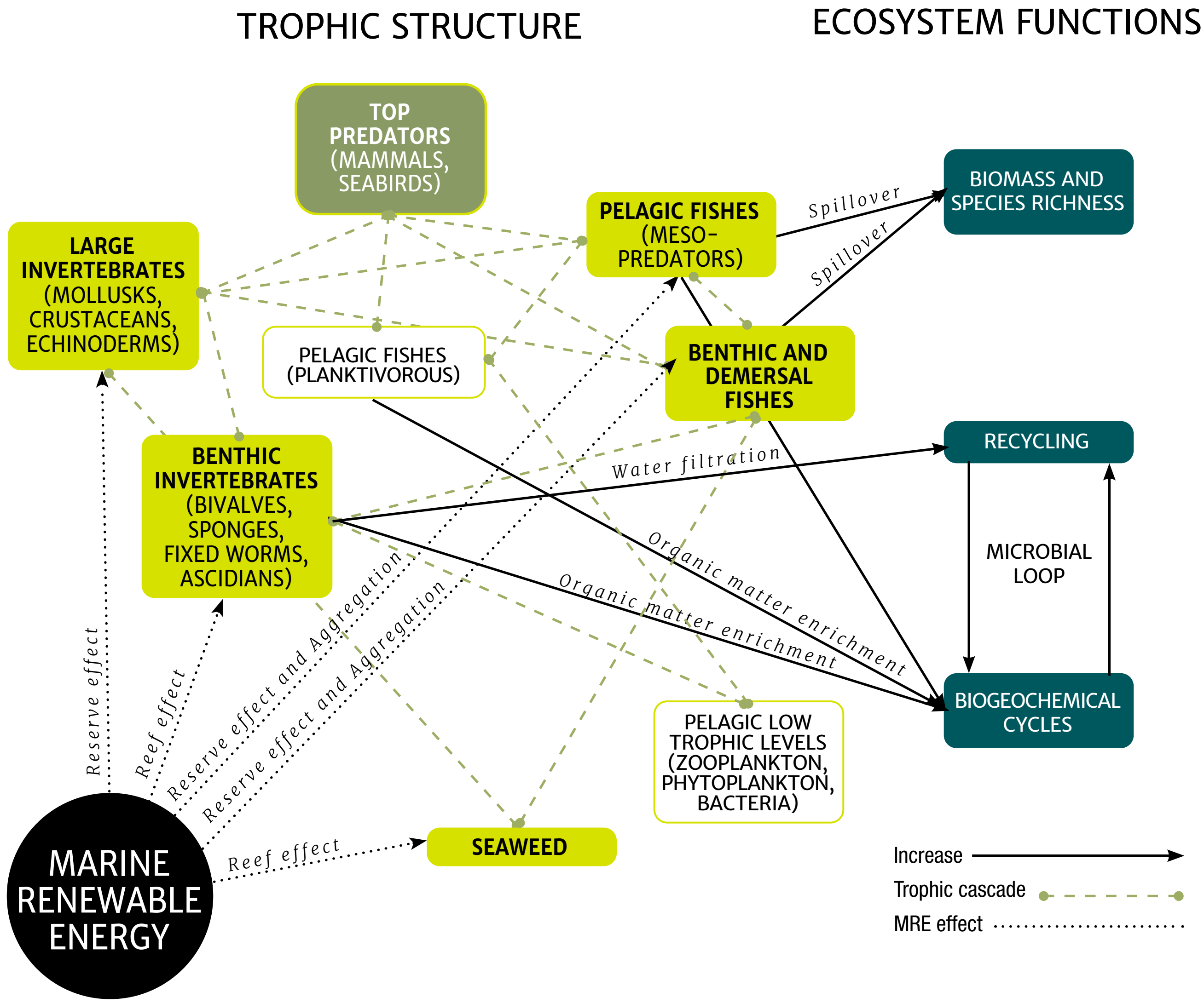

Figure 9.2. Schematic representation of changes in habitats from marine renewable energy (MRE). The effects are represented by arrows, with direct effects and ecosystem compartments directly affected shown in bold. The trophic cascade is presented in a different color than the responses for ease of interpretation.

or Atlantis, could be useful for answering questions around MRE (Shin and Cury 2004; Genner et al. 2010). In addition, MRE projects will be developed in coastal ecosystems that are already subject to pressures from climate change, such as rising seawater temperatures, ocean acidification, hypoxia, and disruption of nutrient cycling. In turn, such pressures contribute to changes in the physiology and fitness of organisms, and shifts in species abundance, distributions, and phenology (Poloczanska et al. 2016). These interacting pressures should be taken into account for future MRE planning, notably through adaptive management strategies that preserve the resilience of important species and the ecosystem as a whole (Engler 2020; see Chapter 6).

Many ecosystem models used to study the influence of climate change on marine communities and food webs (Tittensor et al. 2021), such as size-based and coupled physical-biogeochemical models, could be applied to MRE. Furthermore, MRE sites may be used for multiple purposes, such as aquaculture or tourism, which may enable the co-development of other activities alongside MRE projects (Garavelli et al. 2022). The ecosystem approach and associated tools can be used to study the combined effects of pressures from varying activities at the same site to help define the best management strategies (Le Marchand et al. pers. comm).

9.2.4. CONTRIBUTIONS TO UNDERSTANDING SYSTEM-WIDE EFFECTS

In many parts of the world, the application of an ecosystem approach to MRE has not yet been considered. However, the tools to support an ecosystem approach relevant to MRE already exist and are being used routinely for managing fisheries, offshore wind farms, climate change, and various other assessments of the marine environment, as described above (see 9.2.2). When MRE devices are installed in ecosystems already subjected to natural and/or various anthropogenic pressures, the cascading responses can be difficult to anticipate. The models developed in support of an ecosystem approach for other ocean uses recreate the local food web and environmental parameters to accurately model the effects of a set of pressures on a particular site. Because of this, they are particularly well suited for creating scenarios for the expansion and management of MRE, considering local issues specific to a project site. To facilitate the application of an ecosystem approach to the MRE context, five important points should be addressed in the near future: (1) continue the ongoing consolidation of knowledge on the potential effects of MRE devices and arrays on their surrounding environment to provide risk mitigation strategies (Copping & Hemery 2020); (2) improve the quality of the fine-scale and local data integrated into models; (3) consider differences in the spatial and temporal scales of impacts (Hasselman et al. 2023); (4) consider the uncertainty in ecosystem models (Geary et al. 2020); and (5) couple models and approaches to achieve a holistic ecosystem approach.

Ecosystem management involves understanding the complex interactions between organisms, processes, and scientific disciplines. By providing an overview of the system and its pressures, ecological models and indicators enable the development of scenarios and contribute to the execution of management plans created in collaboration with decision-makers, accounting for a larger context of multiple-use management with potential for cumulative environmental effects (Declerck et al. 2023; Fulton et al. 2019). Since the Convention on Biological Diversity defines human societies as an integral part of the ecosystem, the ecosystem approach considers that ecosystems and human societies are intricately linked and supports integrated studies. However, most applications of the ecosystem approach so far have been based solely on ecological components, due to a lack of knowledge regarding the consequences of ecosystem changes on societies through the relationship between people and the environment. A true ecosystem-based approach requires interdisciplinarity between ecological and social sciences, which can be lacking for the marine environment (Causon and Gill 2018), although this more rounded approach has been growing in application, particularly over the past couple of decades (Trifonova et al. 2022). Nevertheless, while many obstacles remain to be addressed and overcome, the ecosystem approach is a powerful tool for guiding decision-making related to MRE development with a broader view of the potential effects at the ecosystem level.

9.3. CUMULATIVE EFFECTS

This section is a summary of a study in preparation (Fulton et al. pers. comm.) in which the authors assessed the application of a cumulative effects approach to the MRE context by leveraging the lessons learned from its application to other marine sectors.

9.3.1. THE NEED FOR CUMULATIVE EFFECTS ASSESSMENTS

Changes to ecosystem components brought about by the combined influence of past and present human actions (including climate change) are referred to as cumulative effects. Sequential or overlapping activities cause interactions to occur over space or through time in a single location, leading to cumulative effects. These activities may result from various aspects of a single development, multiple developments of a single type (e.g., multiple independent MRE developments in a region, or the construction of an array), or they may result from interactions between various sectors (e.g., fisheries, tourism, shipping, MRE, conservation, etc.). Cumulative effects arise in a variety of forms and can be categorized as additive or nonlinear (i.e., not the same as the sum of the individual pressures added together). Most of the variation observed among the different types of cumulative effects is associated with how nonlinear effects can be expressed (Figure 9.3; see also Section 9.1.2): one pressure may be dominant (thereby masking other effects); pressures may have a synergistic effect, producing a result that exceeds the sum of the individual effects; or pressures may interact antagonistically, producing a result in which the total effect is less than the sum of the individual influences.

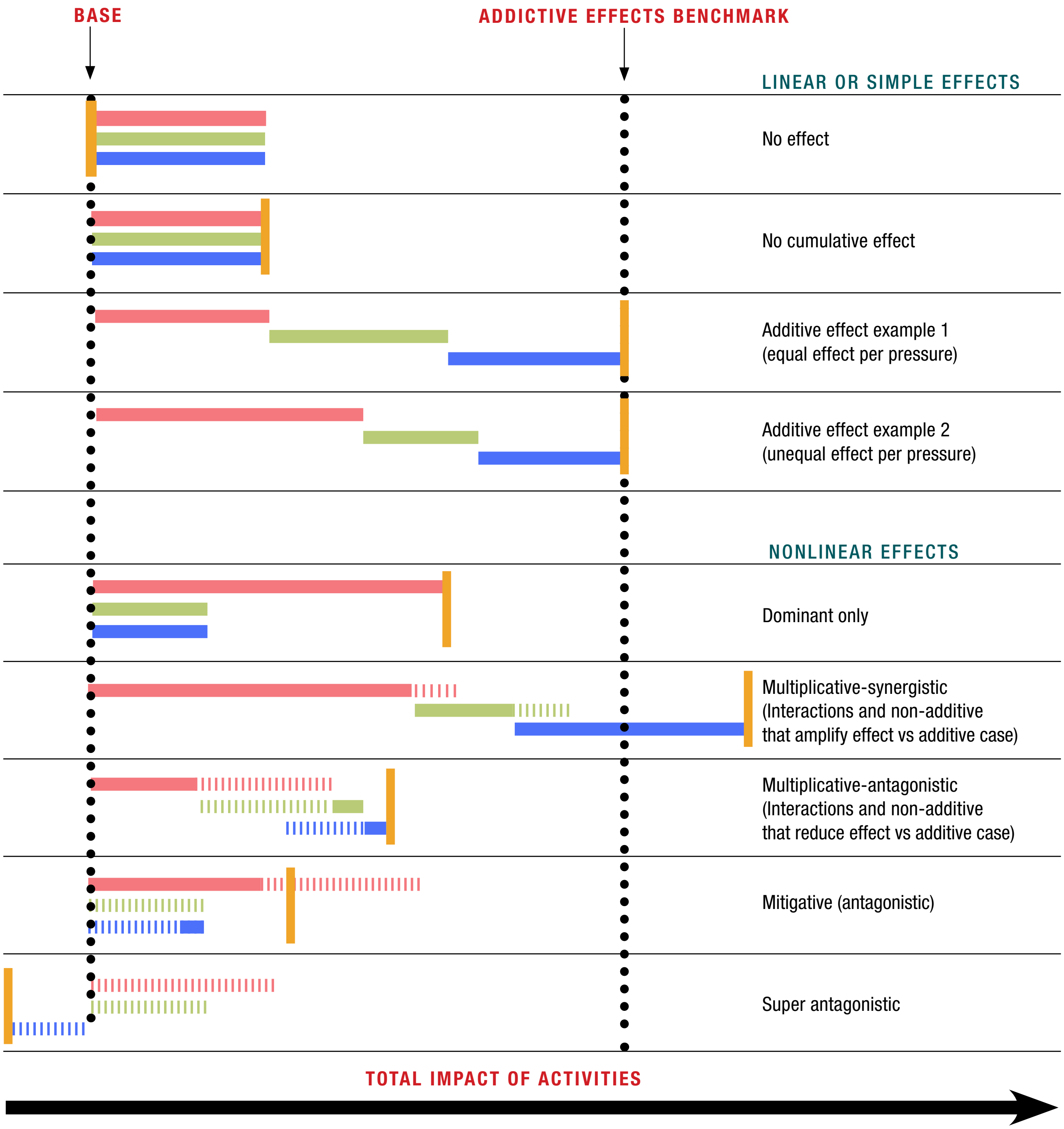

Figure 9.3. Schematic of the different types of non-cumulative and cumulative (additive and nonlinear) effects. Nonlinear effects are marked by interactions (hashed areas on each bar), meaning the outcomes do not simply add up to the linear sum of the individual effects. The no-effect and additive-effect benchmarks are shown as vertical black dotted lines where the levels resulting from other effects are cleared. (From Fulton et al. (2023) and modified from Halpern et al. (2008a))

A cumulative effects assessment (CEA), also called cumulative impacts assessment (CIA), is currently required in many countries for new offshore activities, including MRE development, as the maritime environment is increasingly utilized. In these jurisdictions, a project-level CEA is required as part of a consent application (i.e., as part of an environmental impact assessment [EIA]). Separately, researchers or government agencies may undertake a broad-scale CEA as part of a planning process, as multiple activities and phenomena of different kinds (e.g., MRE, offshore wind, fisheries, aquaculture, shipping, and climate change) can lead to compound (cumulative) effects, which means integrated strategic CEAs are necessary to assure marine use is sustainable in the long term.

Despite these demands for CEAs, there is typically a lack of guidance on the format and the critical role that a well-executed assessment may play in averting future conflict and issues. The benefits of a well-executed CEA are becoming increasingly recognized by regulators, practitioners, and researchers. Due to the absence of historical guidance on CEA content, practitioners have struggled to define what exactly constitutes a CEA. The issues surrounding and necessity for CEAs are increased by the dynamic character of marine ecosystems and the swift expansion of the maritime industries. Another complicating factor is that while the two different forms of CEAs (project scale and strategic scale) share fundamental concepts and workflow steps (e.g., scoping and hazard analysis, data gathering, consultation, analysis, management plans, and responses), they usually have vastly different scopes and use different tools.

Note that while academia (and some national jurisdictions) treat "cumulative impacts" and "cumulative effects" interchangeably—now more commonly using the term "cumulative effects", acknowledging that not all outcomes are necessarily deleterious—this is not universally the case. In some jurisdictions, particularly in the United Kingdom and the European Union, the terminology is not as interchangeable, with "impacts" resulting from the influence of an "effect" (i.e., an event or activity) on the receptor (e.g., ecosystem component). This is one of many instances where there are divergences around terminology and methodology between jurisdictions, practitioners, and academics.

9.3.2. APPROACHES AVAILABLE TO INVESTIGATE CUMULATIVE EFFECTS OF MRE

Expansion of urban and industrial developments on land in the 1970s and 1980s first drove a need to address cumulative effects (Cooper 1998). Between the 1980s and early 2000s, standardizing tiered-assessment approaches became the industry standard (Hope 2006). For example, CEA is a systematic method for identifying and evaluating the compound effects of multiple pressures or activities. Interest in marine CEAs rose sharply in the 2000s as compound pressures caused more conflict and as new analytical assessment methods were developed (Callahan & Sexton 2007; Samhouri & Levin 2012). Still, the broad scope demanded by such large-scale assessments resulted in data limitations that often precluded more quantitative approaches (Stelzenmüller et al. 2018).

Thus far, a portion of the techniques available for CEA have been used for MRE-relevant assessments, such as dynamic approaches, map-based methods, expert elicitation, and loop analysis. Map-based methods are most frequently used in industry applications, which overlay activities (and associated pressures) on ecosystem components, highlighting any potential hotspots (i.e., where multiple activities overlay multiple vulnerable species and habitats [Bergström et al. 2020; Garavelli et al. 2022]). These maps are a reasonably interpretable product that, when done well, can provide the transparent analyses increasingly demanded by the growing list of stakeholders interested in the true sustainability of the growth of marine industries.

Academia also makes use of geographic information system (GIS)-based approaches (e.g., Halpern et al. 2008b; O'Hara et al. 2021) because of their ease of use, even though it is widely acknowledged that these methods do not address a sizeable portion of known marine effects (Crain et al. 2008; Hodgson & Halpern 2019; MacDonald 2000).

A broader set of tools is used within academia, particularly within the analytical steps of a CEA. One of the most used approaches remains expert elicitation (also known as expert judgement). This may be the opening step of a larger process (i.e., the hazard analysis step) or it may be the entire analysis. In most instances, experts are asked to identify connections between activities or drivers and associated stressors, and then they may be asked to score aspects such as the likelihood of the stressor occurring, the level of exposure of each ecosystem component to the stressor, or the sensitivity of the components to the stressors (e.g., Singh et al. 2017).

Quantitative tools are becoming more commonly used. Among the most straightforward to apply are quasi-quantitative methods such as loop analysis, which uses network and flow diagrams to map the important connections and feedback in the system, especially around offshore energy generation or around ecosystem functioning (Niquil et al. 2021; Raoux et al. 2018). This is a very flexible approach that brings together different knowledge and information types and can project the possible effects of expansion or contraction of an activity (e.g., increase development of energy generation infrastructure) on other parts of the system.

Fully quantitative model-based approaches are also being used for a subset of consenting, construction, and development-related questions. For example, ecosystem models such as EwE (historically used to consider fisheries and conservation questions) are being applied to address question around multi-use platforms off Scotland that include both aquaculture and MRE (Serpetti et al. 2021). This method has been expanded upon to forecast possible future cumulative effects within the existing development timelines. These simulation-based approaches—or, alternatively, GIS-based approaches—enable to highlight trade-offs in terms of achieving environmental and other objectives. They can be used to explore co-designed (as in collaboratively defined) scenarios around alternative development and spatial planning options and the deployment of MRE within a multi-sector, multi-use waterway context.

As users of simulation models and other highly quantitative methods can struggle to find sufficient data to support the methods reliably, hierarchical methods that attempt to maintain ease of use, while incorporating a quantitative understanding of indirect effects and feedbacks, are under development (Fulton et al. 2023). More recently, the need for repeatability and transparency for planning purposes has also seen a growing number of research and assessment groups working on novel integrative methods. Many of the most easily accessible tools (e.g., Tools4MSP, Symphony, and the other tools listed in Casimiro et al. [2021]) are often aimed more at strategic CEAs rather than project-level CEAs.

The nascent nature of many MRE projects and the relative newness of more in-depth CEA in planning and EIAs mean few applications go beyond the hazard analysis step (i.e., identifying what may pose a cumulative risk) to evaluate actual risk or realized effect. This is partially because they are usually applied in proactive planning, before developments are approved, rather than in post-deployment assessments, which take place after a development is implemented and the footprint is monitored over time. Moreover, the relative youth of MRE has not allowed sufficient time to monitor changes over time.

Implementation of project-level CEAs has also been mixed. The most cursory of assessments use expert opinion and statements such as "no significant cumulative effects anticipated". In other jurisdictions (such as the Netherlands), clear mandates exist from regulatory agencies (and across sectors) requiring the nesting of project-level CEAs within regional CEA contexts. The quality and consistency of CEAs will improve for MRE and other offshore industries once more jurisdictions have consistent terms of reference, and terminology across assessments and sectors are routinely applied (Hague et al. 2022). Appropriately rigorous, standardized methods that fit naturally within a regional context would minimize poor public perception, legal frustration (e.g., when judicial reviews and lawsuits are put forward by interest groups dissatisfied with the rigor), and the potential for undesirable environmental outcomes witnessed as a result of variable quality of CEAs undertaken in the consenting processes of other industries.

Cross-scale problems that plague CEAs and the system-level evaluation of MRE could be addressed by standardized and coordinated data collection during assessments, with results widely shared. If not addressed, these problems will only get worse as multi-user marine spaces become more crowded and access contested. Such a system-level approach would assure that industry- and society-wide benefits arise from investment in monitoring data.

9.3.3. APPLICATION OF CUMULATIVE EFFECTS ASSESSMENT TO THE MRE CONTEXT

The paucity of detailed supporting knowledge on marine ecosystems and cumulative effects and the complicated nature of comprehensive CEA mean that the most commonly used approaches must simplify one or more dimensions of the assessment to make the task tractable, especially when data availability and accessibility are an issue (Verling et al. 2023). For example, they might concentrate on a smaller number of interacting sectors, a smaller spatial and temporal scope, or decide not to take nonlinear interactions or indirect effects into account (Korpinen & Andersen 2016). Few studies exploring MRE development also consider various other maritime sectors and their trade-offs and relationships, either during the hazard analysis stage or during the more quantitative assessment or planning stages (Turschwell et al. 2022; Turschwell et al. 2023).

Further development of MRE-specific considerations in CEAs is needed, along with addressing priority data gaps, refining assessments in a cost-effective manner, and learning from the greater body of integrated ocean management work. Recommendations stemming from reviews of MRE-relevant CEAs include:

- Multiple stressors from multiple MRE and non-MRE activities or sources need to be considered; this will require connecting project-level and strategic-level planning-oriented CEA processes.
- Relevant and proportionate approaches should be standardized across projects, sectors, and jurisdictions.
- Framing and context (e.g., scales, environmental drivers, human activities, pressures, and ecosystem components) must be transparent with clear documentation.
- Risk criteria need to be set in conjunction with stakeholders and decision-makers prior to any analyses, as well as be project- or plan-specific, based on the best available science, and proportionate to the project or plan to be assessed.
- Where possible, predictive models should be used to assess cumulative effects, acknowledging caveats and surrounding uncertainties for the chosen approach. If this is not possible and/or proportionate, professional judgment (or expert elicitation) should be based upon the best available science and transparently documented (i.e., there must be a clear description of the CEA method used).
- Assumptions made during the CEA and any uncertainties, knowledge gaps, and associated assessment confidence must be communicated clearly and transparently.

Despite progress made to date, significant knowledge gaps remain, most importantly how to assess nonlinear interactions clearly and cost-effectively, especially across drivers and sectors. This relates not only to the technical methods but also to who should participate in the assessments (e.g., extent of involvement with communities, traditional owners, other industries, etc.) and how the results—including the uncertainties—should be explained to non-technical audiences. Stelzenmüller et al. (2020) identified common factors that lead to uncertainty in assessing cumulative effects:

- **Context** – the policy drivers for the CEA (such as the problem framing stage and boundaries established by policies and legislation) and defined risk criteria against which the cumulative effects are judged (which may be established by project assessment terms of reference)
- **Cause-effect (impact-response)** – ambiguity regarding causal linkages and externalities outside the immediate CEA context
- **Inputs** – information on ecosystem components, the efficiency of any management methods being taken into consideration, or the pressures and their associated effects that constitute the basis of the assessment
- **Recognized ignorance (also known as structural uncertainty)** – a fundamental lack of clarity on the system's true relationships and mechanisms and how they are represented in the CEA
- **Knowledge** – this reflects uncertainty due to information gaps and might be resolved by focused research or data collection
- **Variability** – due to a system's inherent variability (e.g., seasonal, interannual, interdecadal)
- **Statistical (analytical) uncertainty (or parametric uncertainty)** – often addressed by sensitivity analysis
- **Scenario uncertainty** – around the variety of potential configurations and results of development, planning, and management that are taken into consideration

Although conveying uncertainty can be challenging, Stelzenmüller et al. (2020) offered strategies for handling it effectively and suggest a method similar to that of the Intergovernmental Panel on Climate Change (IPCC 2022), in which a confidence matrix is provided to represent the reliability of the process and the data that forms the foundation of the CEA. Following these recommendations and applying the lessons learned from other industries' CEAs will enable avoiding repeating past errors and make for a more efficient implementation of CEAs in the MRE context.

9.3.4. CONTRIBUTIONS TO UNDERSTANDING SYSTEM-WIDE EFFECTS

As MRE continues to expand and scale up, the number of project- and strategic-level CEAs is likely to grow. MRE-related assessments will benefit from CEAs in other sectors, including integrated ocean management.

CEAs are founded on understanding system connections, processes, and responses. Lessons from more established industries (e.g., fisheries, conservation) strongly suggest that such assessments have helped avoid outcomes and decisions that preclude future opportunities. CEA experience from other industries suggests that, while map-based methods are simple and rapid, more dynamic model-based analyses would be preferable for long-term, large-scale MRE projects. These analyses allow for more in-depth quantification and consideration of risks that are non-stationary and evolving across many system properties. These dynamic modeling platforms can consider indirect effects, but the effort is considerably more resource- and data-intensive than the additive assessments. Using system-scale models during the early planning stages and periodic review cycles based on more specialized and focused models can help manage resource demands without sacrificing the power of the modeling approaches, as demonstrated by long-term experience from other fields, such as fisheries (e.g., Plagányi et al. 2014). Using models in this way requires fewer resources to apply and means quantitative methods can be used more frequently within an adaptive process to update understanding or recommended responses for specific species or activities of concern.

Although seldom used in the past, semi-quantitative or quantitative models can be used to examine indirect effects; for example, the most commonly used GIS-based methods assume additive but otherwise independent effects (Halpern et al. 2008b; Jones et al. 2018). This is partially due to the lack of observational data on the compound and cascading effects of the many stressor-receptor interactions associated with MRE and other uses of the marine environment. This will need to change in the near future as research on the shifts and consequences caused by climate change has revealed that not only may individual stressor-receptor interactions be non-linear, but that the existence of additional factors may alter a relationship and magnify outcomes (IPCC 2022).

9.4. CONCLUSION AND RECOMMENDATIONS

Marine ecosystems worldwide are facing growing pressures, especially from climate change and human activities at sea, and although the MRE industry has set out to reduce reliance on fossil fuels and therefore mitigate the impacts of climate change, the installation, operation, and decommissioning of MRE devices in the marine environment cannot be left out of the picture. As arrays of MRE devices are deployed in multi-user marine spaces, there will be a need to assess the environmental effects in the context of other anthropogenic activities (e.g., other MRE developments, other energy industries, fishing, shipping, tourism, etc.). The pressures from MRE single devices and large-scale commercial arrays on the marine environment can be placed in a system-wide context by using the ecosystem approach and CEA methods described in this chapter, as well as the framework established to investigate the environmental effects of scaling up to arrays. However, these approaches can be challenging to implement, especially due to the lack of necessary data, and some may not be cost-effective; thus, assessments need to be proportional and risk based.

While stressor-receptor interactions have, to date, been studied mostly in isolation from each other, MRE devices are installed within functioning ecosystems and food webs, where the effects of a single stressor-receptor interaction may impact other components of the system, through top-down and/or bottom-up cascading effects. However, there is currently little, if any, information available on compound and cascading effects from the different stressor-receptor interactions; desktop and field studies are needed to investigate these impact-responses. Future research endeavors need to focus on the associations between various stressor-receptor interactions and their cumulative effects, especially in the context of multiple anthropogenic activities within a region and/or over time. Applying the approaches and framework described herein would assist with determining these system-wide interactions and contribute toward a more comprehensive understanding of the environmental effects of MRE technologies.

Moreover, improvements are necessary regarding scientific knowledge and the quality of numerical models in order to efficiently apply a system-wide approach to the MRE context; however, different priorities should be given to the various improvements needed as laid out in Figure 9.4. As described in Chapter 3, numerous knowledge gaps remain in our basic understanding of the effects of the stressor-receptor interactions, especially on animal behavior, physiology, and fitness. Few stressor-receptor interactions to date have been investigated in the context of climate change; the effects of changes in habitat or oceanographic systems and of displacement due to MRE may become challenging to discern from those of climate change. Similarly, other activities at sea may enhance, override, or mask some of the environmental effects of MRE, such as those from the exposure to underwater noise or EMF emissions. Existing numerical models need improvement to be able to investigate these effects in a system-wide approach. In addition, it is crucial to strive for a complete understanding of an ecosystem's initial state, as well as the collection of fine-scale and local data to adequately represent all MRE-environment interactions with a modeling study. Numerical models must be able to account for these site and ecosystem specificities, which may come in the form of very large and complex datasets. Lastly, with the expansion to large-scale commercial arrays and MRE projects that will be operational over decades, it is essential to understand how environmental effects may encompass larger spatiotemporal scales. Therefore, numerical approaches and frameworks must be able to model the effects at different scales. Only then will the numerical tools provide a probabilistic approach to investigate the system-wide effects of MRE development.

Nonetheless, and despite these necessary improvements, tools are currently available for the MRE community to start applying a system-wide approach to existing and upcoming MRE projects, keeping in mind the caveats listed above. Most importantly, researchers and practitioners should be as transparent in their processes as possible, and share data, results, and uncertainties publicly, in order to facilitate more comprehensive and informed investigations, reduce duplication of efforts, and increase the overall confidence and trust in MRE research outcomes.

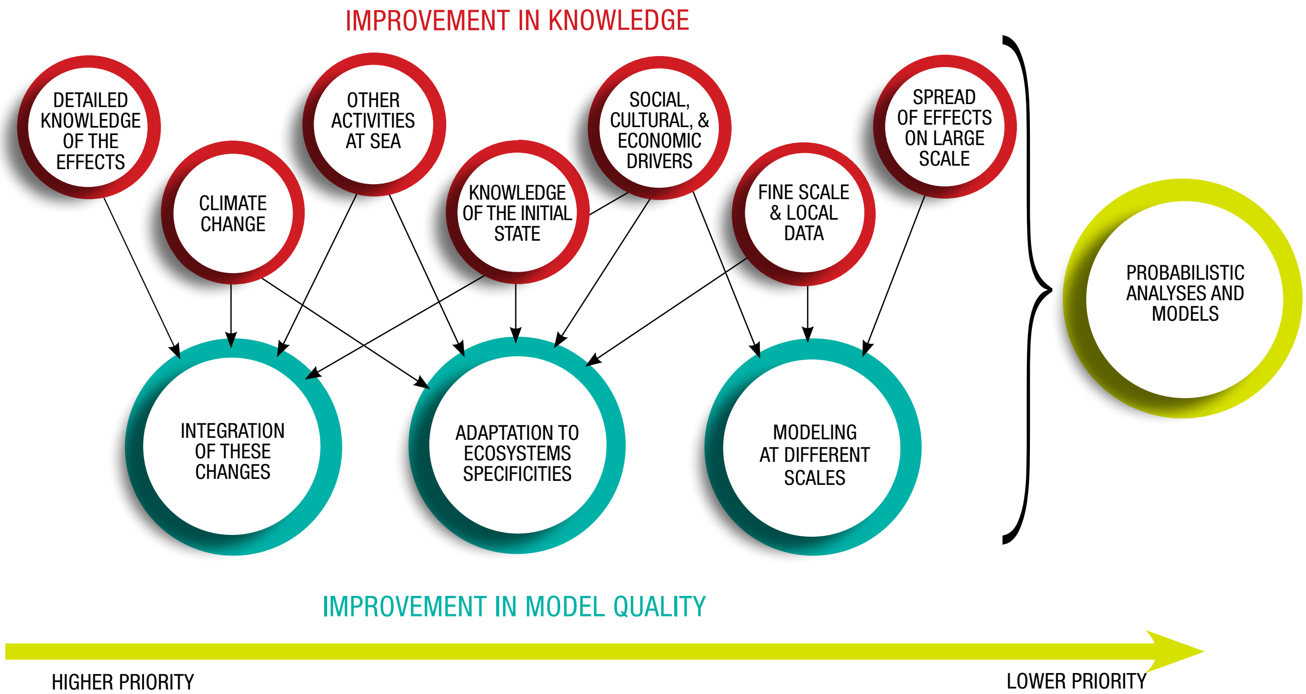

Figure 9.4. Different priorities should be given to improving knowledge and model quality, as they need to be carried out to model system-wide environmental effects of marine renewable energy.

Recommendations for advancing the implementation of a system-wide approach to understanding the environmental effects of MRE include:

- Improving the general understanding of physical and biological processes, ecosystems' characteristics, and social and economic factors in regions targeted for MRE development;
- Identifying MRE-specific data gaps that prevent applying a system-wide approach and a path toward collecting these data (e.g., laboratory experiments, field observations, etc.; see Chapter 3);
- Considering uncertainty in all modeling efforts for credible management decisions;
- Adapting system-wide investigations to MRE projects' lifecycle stages (e.g., construction, operation, decommissioning) and to specific scientific questions and management needs;
- Identifying thresholds in responses to the stressor-receptor interactions and tipping points past which system-wide effects may become irreversible; and
- Advocating for increased international cooperation and funding, which are essential to supporting data availability and science-led system-wide environmental effects assessments that can translate into lifting barriers to consenting MRE arrays.

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Suggested citation:

Hemery, L. G., Hasselman, D. J., Le Marchand, M., Safi, G., Fulton, E. A., Copping, A. E. 2024. Beyond Single Marine Renewable Energy Devices: A System-wide Effects Approach. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 226-250). doi:10.2172/2438598

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Potential Environmental Effects of Marine Renewable Energy in Tropical and Subtropical Ecosystems

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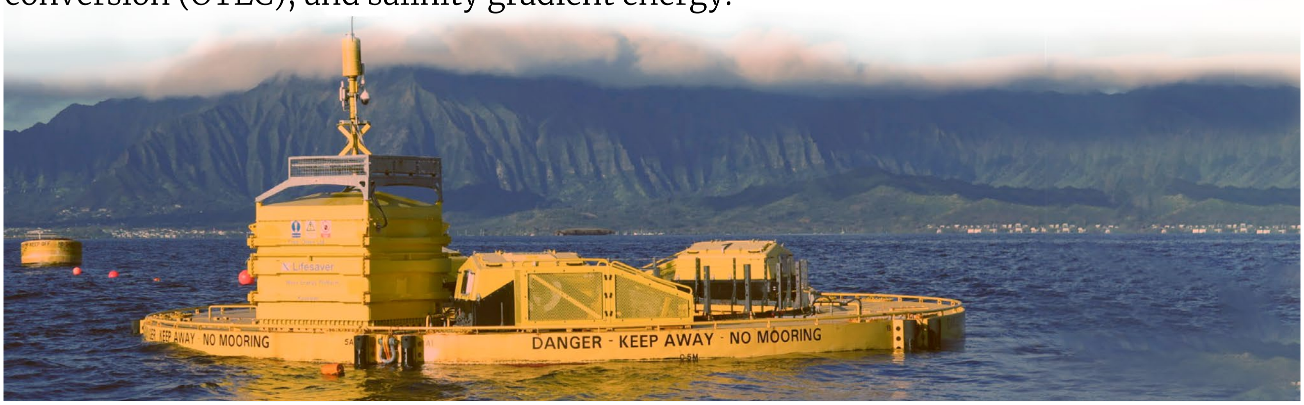
Marine renewable energy (MRE), such as wave, tidal, ocean current, and thermal and salinity gradient, is under development in many parts of the world. However, studies examining the environmental effects of MRE have primarily focused on deployments in temperate regions and countries in the Northern Hemisphere. As MRE development expands into tropical and subtropical countries (between 35°N and 35°S), there is a need to examine the potential environmental effects specific to these regions and their unique habitats and species. Unlike temperate regions where wave and tidal energy resources dominate, tropical and subtropical regions can leverage five different types of MRE: wave energy, tidal energy, ocean current energy, ocean thermal energy conversion (OTEC), and salinity gradient energy.



While wave energy resources are generally much lower around the equator than in temperate regions, it is typically greater in subtropical regions than tropical regions (Rusu & Rusu 2021). Hotspots for wave energy within subtropical and tropical regions include Western Australia (Wimalaratna et al. 2022), South Africa (Lavidas & Venugopal 2018), off the west coast of South America (Eelsalu et al. 2024; Lucero et al. 2017), Southeast Asia (Li et al. 2022), and around islands in the northern and southern Pacific Ocean (García Medina et al. 2023) and southern Indian Ocean (e.g., Mauritius (Kamranzad et al. 2022)). As the MRE industry advances, developments in these tropical and subtropical regions may be considered. Several tropical and subtropical areas also have tidal resources, such as the northern coast of Brazil (González-Gorbeña et al. 2015), the western coast of Central and South America (e.g., Colombia (Osorio et al. 2016)), the northwestern coast of Australia (Penesis et al. 2020), and the western coast of Africa (Hammar et al. 2012). Several channels and straits in Southeast Asia present good tidal resources as well, particularly in Indonesia (Firdaus et al. 2020) and the Philippines (Abundo et al. 2023). Harvestable ocean currents are generated further offshore than tidal streams, from large currents like the Gulf Stream. The strongest ocean currents are generally located in tropical and subtropical areas, off the coast of Florida and in Asia from Japan to the Philippines (Barnier et al. 2020). Temperature gradients that provide enough thermal power capacity are non-existent in temperate regions but abound in tropical and subtropical regions (Nihous 2010). OTEC uses temperature gradients between warm surface waters and cold deep waters to produce energy. OTEC is especially regarded as a preferred source of renewable energy by tropical island countries with access to cold deep water close to shore (Osorio et al. 2016). Finally, areas with extractable salinity gradient energy resources are located in temperate, tropical, and subtropical regions but the greatest potentials are found along warmer coastlines, especially in the Caribbean Sea and in the Mediterranean Sea (Alvarez-Silva et al. 2016).

Although MRE projects have predominantly existed in temperate regions, some wave, tidal, ocean current, and OTEC projects have occurred over the last several decades in tropical and subtropical regions, with various device prototypes tested and full-scale projects planned or deployed. In tropical and subtropical regions, there have been several successful wave energy deployments over the years, such as the test deployments at the Wave Energy Test Site in Hawaii (United States [US]) and the Perth Wave Energy project (Australia). A few tidal energy projects have also been, or are being, considered in tropical and subtropical regions (e.g., Clarence Strait Tidal Energy Project north of Darwin [Australia], Hydrokinetic Energy in the Florida Keys [US], and Lombok and Larantuka Straits in Indonesia, and San Bernardino Strait in the Philippines). While a few ocean current energy projects are under investigation, notably in Florida and the Caribbean, only the IHI Ocean Current Turbine has been tested at different demonstration scales in the Kuroshio area off Japan, as well as a pilot project off Taiwan. Several OTEC plants are currently in operation (e.g., in Hawaii and Japan) and additional projects are being proposed, planned, or constructed in numerous other areas, including islands in the Caribbean. Finally, the potential for salinity gradient energy has been assessed in some tropical and subtropical regions such as Mexico (Marin-Coria et al. 2021), Australia (Helfer & Lemckert 2015), and Colombia (Roldan-Carvajal et al. 2021). So far, no salinity gradient energy development has occurred in tropical and subtropical regions.

Prior and existing MRE projects in tropical and subtropical regions are relatively sparse and most target wave energy resources (Figure 10.1). China has the highest number of MRE projects with wave, tidal, OTEC, and ocean current technologies, followed by Australia and Japan. Other MRE projects have been located in Bermuda, Chile, Mexico, French Guyana, Madagascar, Togo, Israel, South Korea, Indonesia, and the US.

Because of the lack of development and available funding in tropical and subtropical regions, the environmental effects of MRE development are not well studied and could potentially differ from those described in temperate regions. Tropical and subtropical regions host a diverse range of benthic and pelagic habitats such as coral reefs, mangroves, and seagrass beds that provide feeding, breeding, spawning, and nursing grounds for a wide variety of marine animals, including commercially important, endangered, and keystone species (Figure 10.2). Because many of these animals and habitats are already experiencing the disproportionate impacts of climate change, MRE development in tropical and subtropical regions may present additional risks that could contribute to reduced biodiversity and ecosystem resilience (Felix et al. 2019). Tropical and subtropical

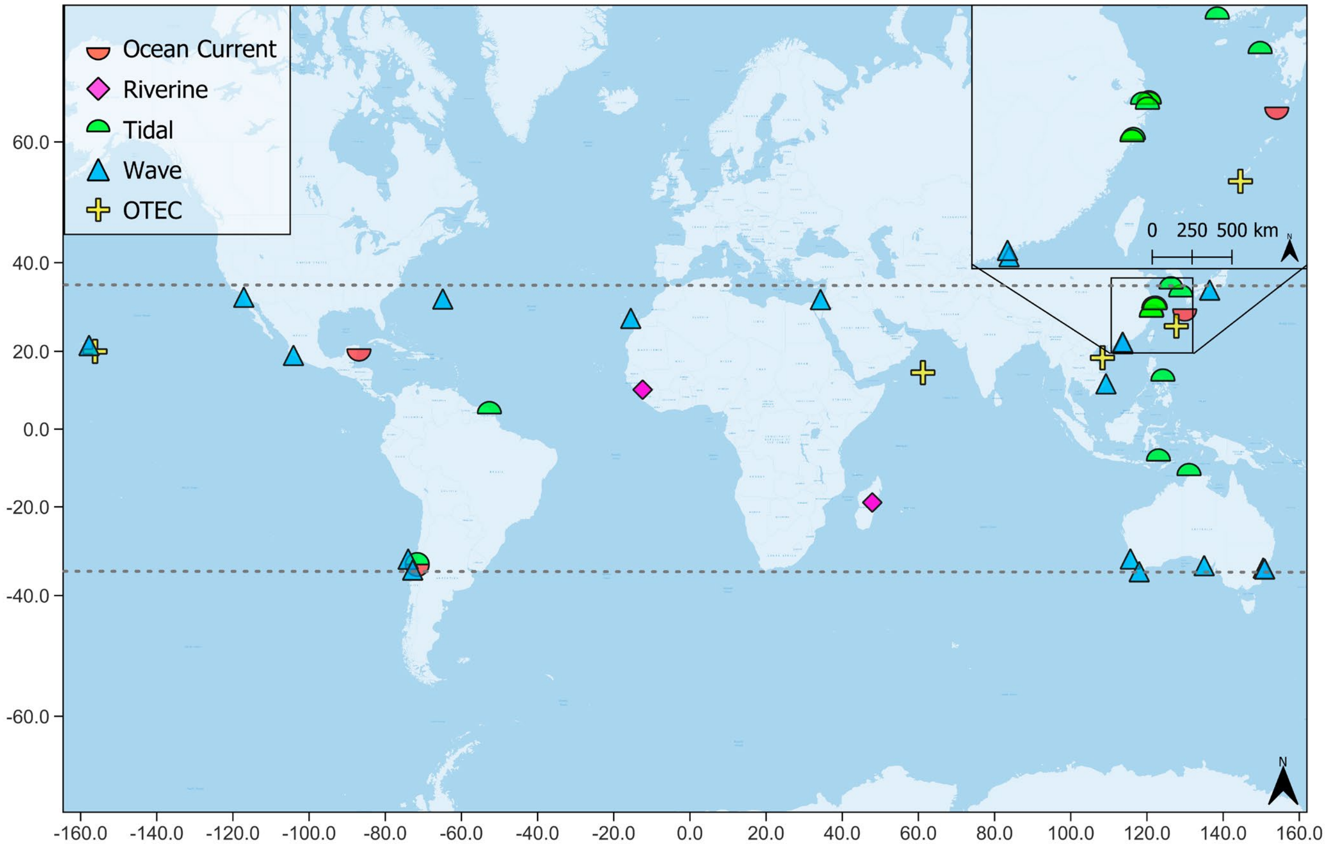


Figure 10.1. Marine renewable energy projects (ongoing, completed, canceled, planned) in tropical and subtropical countries, by technology type. The inset map highlights projects in China, Japan, and South Korea. Dashed lines represent the latitudinal range (35ºS to 35ºN) for the subtropical and tropical regions. Source: Tethys.

ecosystems also provide a variety of ecosystem services such as storm protection, recreational activities (tourism, fishery), and habitat for Indigenous communities (Moberg & Rönnbäck 2003). Mitigating environmental effects of MRE on these ecosystems is also important to support these benefits.

It is important to note that the adoption of suitable MRE technologies in tropical and subtropical regions will play an essential role in mitigating and adapting to the impacts of climate change. Deployed responsibly, MRE has the potential to make a substantial contribution to the provision of sustainable energy for communities and to the decarbonization of the wider energy system. This requires a better understanding of how environmental effects may differ between tropical/subtropical and temperate regions, to adapt, if necessary, technology and supporting infrastructure, operations, environmental mitigation, monitoring, and management methods. To begin addressing this need, Ocean Energy Systems (OES)-Environmental has expanded its research on the environmental effects of MRE to tropical and subtropical regions. The information presented in this chapter derives from a literature review, answers to a public survey, feedback collected from workshops, and interviews with experts in the field. The detailed methodology to collect the information as well as the public survey and interview questions are both available online as supplementary material. The public survey, available in both English and Spanish, requested information on any ongoing or emerging MRE projects in tropical and subtropical ecosystems, any research, monitoring, or modeling efforts that may be relevant, any relevant literature or other resources of information, and any specific contacts and/or organizations with relevant experience in these areas. The interviews with experts requested similar information as the survey and were also used to identify knowledge gaps and determine future research needs on environmental effects of MRE in tropical and subtropical ecosystems. The information collected on each topic area is covered thematically in the following sections.

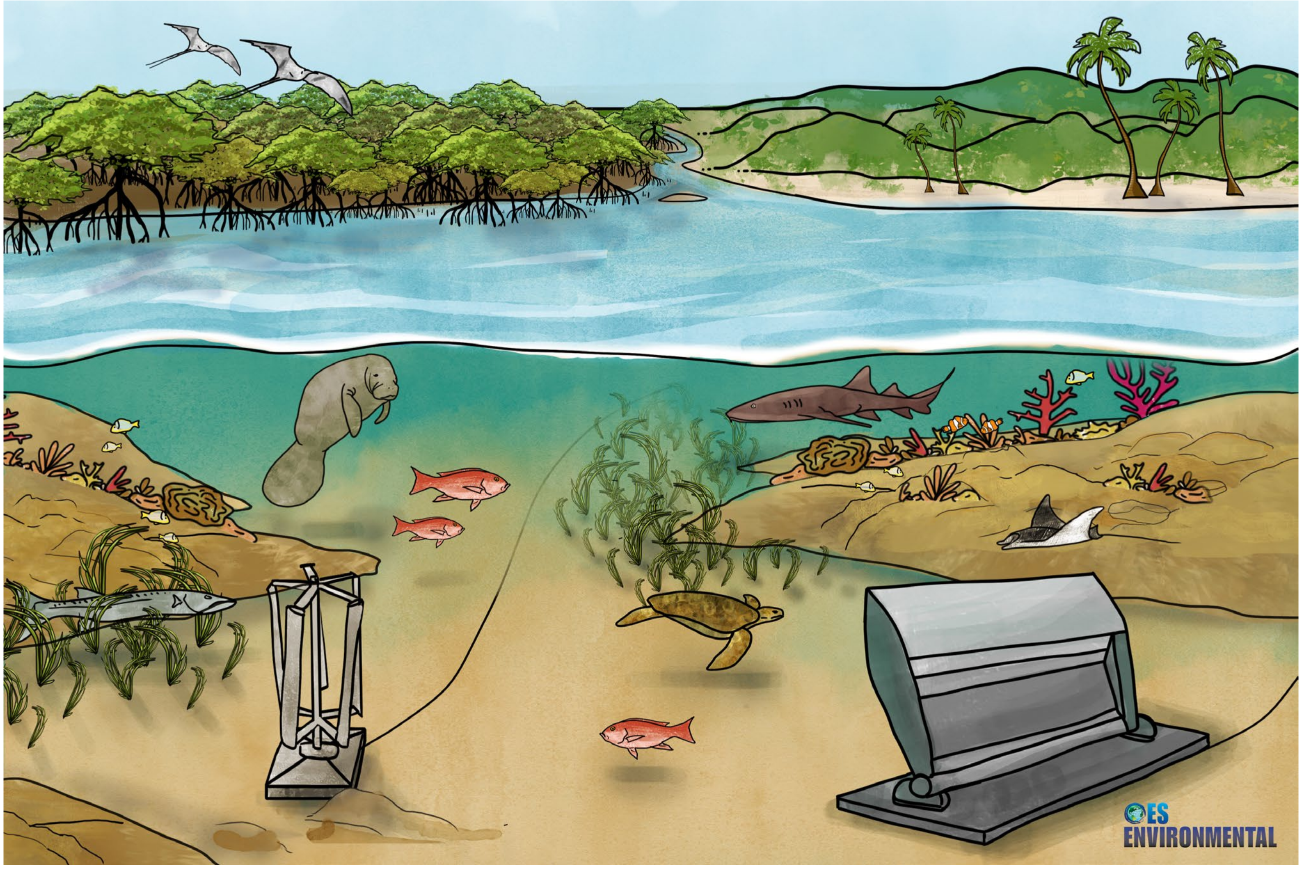


Figure 10.2. Schematic of a tidal turbine and a wave energy converter in a tropical marine ecosystem. (Illustration by Stephanie King)

10.1. STRESSOR-RECEPTOR INTERACTIONS IN TROPICAL AND SUBTROPICAL ECOSYSTEMS

The potential environmental effects of MRE in tropical and subtropical regions can be described through specific stressor-receptor interactions, and consideration of the unique animals, habitats, and ecosystem processes present. These interactions can differ depending on the MRE technology considered.

The potential environmental interactions associated with the development of MRE in tropical and subtropical regions are similar to those identified in temperate regions: collision risk, underwater noise, electromagnetic fields, changes in benthic and pelagic habitats, changes in oceanographic systems, entanglement, and displacement (see Chapter 3). These interactions are specifically relevant for wave, tidal, and ocean current energy, except for collision risk which is only relevant for tidal and ocean current energy. The prevalence and perceived importance of these interactions may differ in tropical and subtropical regions, likely due to the unique receptors susceptible to change. Changes in habitat, underwater noise effects on marine life, collisions between tidal or riverine turbine blades and marine animals, and changes in oceanographic systems were identified by the survey participants as the most important interactions to consider in tropical and subtropical regions.

The potential interactions associated with OTEC are similar to those associated with other MRE technologies (e.g., artificial reef effects and other changes in habitat, changes to migratory routes, entanglement, and pathways for invasive species). However, some unique effects associated with OTEC are those related to the cold water return, the release of nutrient-rich water, the entrainment of marine life in deep cold water pipes, and chemical discharges. The cold deep ocean water brought to the surface for heat exchange in the OTEC process must be returned to the ocean. However, this water could be up to 20°C colder than ambient surface water and could potentially shock organisms if discharged at the surface, or destabilize the stratification of ocean water that maintains warm water at the surface (Giraud et al. 2019). To mitigate these effects, the cold water must be discharged at an intermediate depth so that it is rapidly diluted to match ambient temperatures. The cold water pipe, which pumps ocean water from 800-1000 m below sea level or more in most OTEC operations, also has the potential to suck up and entrain fish or other marine organisms, bringing them up to the surface where they are unlikely to survive the change in pressure or temperature (Lamadrid-Rose & Boehlert 1988; Myers et al. 1986). However, evidence from over eight years of operating the Okinawa Prefecture OTEC facility in Japan indicates that this event is extremely rare (i.e., less than one fish seen per year; B. Martin, pers. comm.). Similarly, the Natural Energy Laboratory of Hawaii Authority OTEC facility in the US has never recorded such an event (L. Vega, pers. comm.), suggesting the frequency of an entrainment event will likely remain below detection, even with targeted monitoring programs. Finally, closed OTEC systems use ammonia or other chemicals as the heat exchange medium, and accidental leakage of these chemicals in gaseous form could be harmful to marine life.

Potential effects from salinity gradient energy technologies are not well studied. One theoretical study performed in the Río Lagartos Biosphere, in the Yucatan Peninsula, Mexico, highlighted potential effects from salinity gradient energy technologies, such as changes in flow and nutrient concentrations that could alter natural ecosystems (e.g., mangroves) and threaten keystone species such as the Caribbean flamingo (*Phoenicopterus ruber*) and the Atlantic horseshoe crab (*Limulus polyphemus*) (Wojtarowski et al. 2021). In the absence of representative pilot projects at megawatt scale for salinity gradient energy, Seyfried et al. (2019) assessed potential environmental effects based on analogies with other coastal facilities sharing similar infrastructure or processes, such as desalination plants or wastewater treatment plants. Unique effects from salinity gradient energy technologies were the impingement and entrainment of organisms because of the intake of both high and low salinity waters and the discharge of chemicals. Currently, there are no known established environmental monitoring programs for salinity gradient technologies in tropical and subtropical regions.

10.2. RECEPTORS OF CONCERN IN TROPICAL AND SUBTROPICAL ECOSYSTEMS

Effects on biodiversity and ecosystem function are commonly identified as the most important concerns for MRE development in tropical and subtropical regions. When examining the environmental effects of MRE in those regions, there is a need to apply an ecosystem approach (see Chapter 9) to consider all species of an ecosystem, as well as their trophic interactions, instead of focusing on a limited number of key species (e.g., sea turtles) (Mumby & Hastings 2008). Several species in tropical and subtropical regions contribute to the high biodiversity of marine ecosystems and are often listed as endangered or threatened (e.g., most species of sea turtles, whales, manta rays, sharks, dolphins, and corals). Consequently, the sensitivity of ecosystems that characterize potential MRE project sites is a common concern in tropical and subtropical regions. For example, in Mexico and Colombia, areas with the greatest MRE resource potentials often overlap with fragile ecosystems. In Brazil, experts expressed concerns around potential effects on coral reef areas during the installation of MRE devices. Coral reef ecosystems are extremely vulnerable and any negative impacts could be potentially irreversible (Cruz et al. 2018; Mumby 2009).

In Latin America, concerns about the effects of underwater noise resulting from pile drilling during the installation of MRE devices on marine mammals have been raised, particularly in Mexico, Chile, and Brazil. In Brazil, such effects of underwater noise have been considered the main potential impact on biodiversity. The significance of this impact makes it one of the most addressed topics in environmental impact assessment (EIA) studies for offshore development in Brazil since whales can become stressed, weakened, and disoriented. Species of concern for MRE development in Brazil include endangered marine mammals (e.g., sperm whale [*Physeter macrocephalus*]), commercially valuable fish species (e.g., southern red snapper [*Lutjanus purpureus*]), many of which are already overexploited or fully exploited, endangered seabirds (e.g., various species of gadfly petrels [*Pterodroma* spp.]), and sea turtles (e.g., leatherback sea turtle [*Dermochelys coriacea]*) (Silva et al. 2022). In the central and northern parts of Chile, there are also concerns about the risk of collision, entanglement, and displacement for seabirds and marine mammals. Marine mammal (e.g., blue whale [*Balaenoptera musculus*]) migration routes might be disrupted by the presence of an array of MRE devices, potentially leading to displacement (see Chapter 3).

In Asia, the potential for displacement of marine animals was also mentioned by the experts. For instance, in Indonesia, a proposed tidal energy project has raised concerns about the seasonal displacement of vulnerable species, such as the ocean sunfish (*Mola mola*). Concerns have also been raised in the Maldives that cetaceans and whale sharks could be displaced from their migration routes. Other concerns around the environmental effects of MRE in Asia are related to effects on coral reefs and tropical marine life, and are associated with changes in habitat, particularly in Indonesia, Vietnam, and Singapore (e.g., changes to fish communities). For tidal projects in the Philippines, effects on coral reefs are less of a concern as developments would be in high velocity current areas with benthic habitat dominated by rocks, algae, and soft coral colonies. Sensitive areas in the Philippines are generally well described and could be suitably avoided when selecting a deployment site.

In Hawaii, experts highlighted that protected and endangered species are the main concern related to potential environmental effects of MRE, particularly related to the risk of entanglement and underwater noise for sea turtles (e.g., hawksbill turtle [*Eretmochelys imbricata*]), Hawaiian monk seals (*Monachus schauinslandi*), and whales (e.g., humpback whale [*Megaptera novaeangliae*]).

In Australia, experts primarily expressed environmental concerns about the effects on benthic communities, fish (e.g., artificial reef effect), and ecosystem processes. Negative impacts on seagrass beds have been observed associated with the mooring of an MRE device. Certain projects have decided to schedule the deployment of their device during the austral summer as they are less likely to have negative impacts on marine mammals due to collision risks; although these deployments could be constrained with cyclone and monsoon seasons.

Beyond the concerns related to environmental effects, the effects of MRE on tropical and subtropical ecosystems could directly influence the services they provide to society and impact socioeconomic systems.

10.3. SOCIOECONOMIC CONCERNS IN TROPICAL AND SUBTROPICAL ECOSYSTEMS

In tropical and subtropical regions, MRE development may have significant socioeconomic effects on nearby coastal and island communities if their needs are not considered during the project planning phase (Borges Posterari & Waseda 2022). These coastal and island communities are often small and isolated, and often rely on expensive diesel fuels for electricity generation or do not have access to reliable electricity (Pandyaswargo et al. 2020). The transition to, or adoption of renewable energy sources has been a recent focus in several tropical and subtropical regions, with an emphasis on social acceptance and economic impacts of MRE (Adesanya et al. 2020; Fadzil et al. 2022; Ramachandran et al. 2021).

As it is often the case with new renewable energy projects, coastal residents may be worried about impacts on local communities and tourism and may not accept MRE projects along their coastlines due to impacts to viewshed or existing uses of the ocean (Hubbard 2009). However, residents may express these issues in terms of environmental concerns instead, often as a result of lack of information, or lack of access to available information regarding the potential environmental effects of MRE. Coastal communities are keen observers of new project developments in their marine space and often participate in development processes, so their social perceptions play a crucial role as their influence can expedite, slow down, or stop projects (also see Chapter 5). Engaging with stakeholders regularly and from an early stage of the MRE project is crucial to assure public support. In Indonesia, public support for a tidal energy project at Larantuka Strait started to rise once the public was aware of the benefits of the project (Ramachandran et al. 2020). The tidal energy project would provide electricity in a region without reliable energy infrastructure, which would positively influence the local community.

More than in temperate areas, coastal communities in tropical and subtropical regions rely heavily on nearshore fisheries to support their economies. For example, the Lafkenche law in Chile, passed in 2008, provides exclusive access rights to coastal areas and resources to Indigenous communities (González-Poblete et al. 2020). A need for new policies has been expressed in Chile to allow the co-existence of artisanal fisheries and MRE, based on potential interactions of MRE devices and their supporting infrastructure with the fisheries. In Vietnam, there is concern that MRE projects could cause negative impacts on the fishing communities' livelihood. Fisheries are also of major importance in Japan and the government will only enable leasing for MRE if an agreement is reached between fishers and MRE developers. Such agreement is developed in consultation with local fishing associations.

The economy in tropical and subtropical countries is often dependent on tourism, and potential conflicts with MRE development could occur (e.g., wave energy developments in key coastal areas popular for surf tourism) (Borges Posterari & Waseda 2022; Fadzil et al. 2022). For example, in Indonesia, the potential displacement of the ocean sunfish associated with the presence of a tidal energy project could result in a reduced number of scuba divers who come from all over the world to observe this species. In Australia, visual impacts of MRE devices are also perceived as impactful to tourism. MRE projects can be halted easily due to negative public perceptions and community opinions if seen as a risk to fishing and tourism activities in vulnerable coastal communities.

Small islands and isolated coastal territories encounter challenges in ensuring reliable access to energy, freshwater, and food while pursuing sustainable development. The imperative to fulfill these needs, coupled with the imperative to address climate change through mitigation and adaptation efforts, has prompted the development of renewable energy systems. A comprehensive solution tailored to the unique requirements of those territories is the concept of an Ocean Technology Ecopark (Osorio et al. 2016). Such a concept could comprise an OTEC plant, diverse applications for deep ocean water use, and a dedicated research and development center. An Ocean Technology Ecopark has been proposed on San Andres Island (Colombia) for implementing OTEC technology, water desalination, and establishing a viable business model for deep ocean water use.

10.4. CASE STUDIES

This section overviews case studies of MRE development in tropical and subtropical regions, aiming to highlight distinctive environmental considerations and associated socioeconomic concerns within these ecosystems. The case studies were selected based on available information about environmental effects of MRE.

WAVE ENERGY IN THE UNITED STATES

The wave energy potential in Hawaii is the highest globally because of the presence of four primary wave types with trade wind waves especially providing a consistent energy resource within the state (Stopa et al. 2011). The island of O'ahu was chosen as the ideal place for a development of a wave energy test site because of its access to the windward direction in Kaneohe Bay (north coast of O'ahu), exposure to the trade wind waves, its access to population centers, and the availability of a shallow shelf (Stopa et al. 2013) (Figure 10.3).

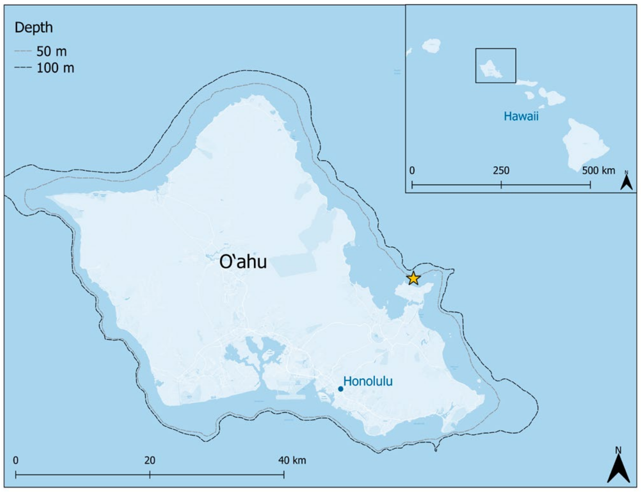


Figure 10.3. Map of the United States Navy Wave Energy Test Site (WETS; yellow star) off the island of O'ahu, Hawaii.

The US Navy Wave Energy Test Site (WETS) has been in operation since 2004 and was the country's first grid-connected wave energy test site. The site includes three test berths at different water depths (30 m, 60 m, and 80 m) and hosts developers to test their pre-commercial wave energy converter (WEC) devices in an operational setting.

Several wave energy devices have been tested at WETS through the years and field monitoring has been conducted to study the potential environmental effects of those devices (Cross et al. 2015; Polagye et al. 2017). Within O'ahu, Kaneohe Bay has a complex estuarine system with a large barrier coral reef, numerous patch reefs, fringing reefs, and several riverine inputs (Aeby 2007; Hunter & Evans 1995). This complex system provides a habitat for numerous species, including those listed on the US Endangered Species Act (ESA) (e.g., scalloped hammerhead sharks [*Sphyrna lewini*]). Types of environmental monitoring that have been considered or conducted at WETS include:

- Acoustic measurements (e.g., active sweeping sonars for monitoring marine mammals and schools of fish);
- Sediment transport measurement/observations at WEC moorings;
- Protected marine species monitoring (e.g., optical and acoustic sensors for active and passive tracking of marine life);
- Water chemistry; and
- Electromagnetic fields.

Ongoing surveys and project/device specific monitoring have been taking place at the site since 2003 with little to no interactions observed with ESA listed species near the site, and no impacts highlighted within reports on ESA-listed species. There was only one sighting of two green turtles (*Chelonia mydas*) in 2019 within the site, but no impacts were recorded. Outside of ESA listed species, the interactions at WETS have been minimal for cetaceans and the site itself has created an artificial reef setting for corals and invertebrates with very little impact on the species. Fish have also benefitted from this artificial reef and the biomass of fish (e.g., bluestripe snapper [*Lutjanus kasmira*]) has been increasing.

TIDAL ENERGY IN AUSTRALIA

Australia is surrounded by great MRE resources, especially waves along the west coast and tidal in the northwest. Clarence Strait, near Darwin in the Northern Territory, was the focus of a tidal energy project and a planned tidal test center (Clarence Strait Tidal Energy Project and Tropical Tidal Test Center) (Franklyn 2008), although now abandoned (Figure 10.4). The strait is located on the Sahul Shelf in the Indo-West Pacific region, between Timor and the Arafura Seas. In the middle of Clarence Strait lies the Vernon Islands group, surrounded by deep channels with strong and complex tidal currents.

Figure 10.4. Map of the tidal energy project and tropical tidal test center (yellow star) in Clarence Strait, Australia.

The northwest continental shelf of Australia presents a rich biodiversity that can be classified into multiple coastal mesoscale bioregions, with its northern region considered part of the "realm of reef-building corals" (Wilson 2013). The Vernon Islands are an important species-rich coral reef and mangrove system, home to an endemic anemone fish (Tiwi Land Council 2013). Surrounding waters are critical habitats for dugongs and sea turtles because of the seagrass and algal beds around the islands. Numerous fish species of recreational value are found in the waters of Clarence Strait, including barracuda, tuna, and golden snapper (*Lutjanus johnii*). In addition, all waters and coastline around Clarence Strait hold cultural values to local First Nations people. Because of these biodiversity and cultural riches, the area has been declared a Conservation Reserve. An Environmental Impact Statement (EIS) was required for the Clarence Strait project to move forward because of numerous concerns due to the knowledge gaps around the environmental effects of tidal energy on tropical ecosystems and the presence of vulnerable species and habitats. Issues of particular concern included:

- Potential impacts on coral reef communities;
- Risks to rare and threatened species and listed migratory species occurring in the impact area;
- Changes to feeding grounds for sea turtle and dugong, with cultural importance;
- Potential impacts on seabed and water quality; and
- Potential impacts on traditional, recreational, and commercial use of the area.

The EIS required baseline assessments of marine vertebrates including mammals, marine benthic invertebrates, terrestrial fauna and flora, physical environment, and socioeconomic aspects (human dimension) (Table 10.1), as well as post-installation monitoring. Literature reviews on potential physical interactions of marine mammals with tidal turbines, as well as acoustic interferences and impacts of turbine noise, were conducted (Franklyn 2008). However, the project was later canceled.

TIDAL ENERGY IN THE BAHAMAS

The Bahamas is a country consisting of more than 700 islands, cays, and islets of which only 28 are populated. Like many island countries, the Bahamas almost entirely relies on imported fossil fuels, leaving it vulnerable to global price fluctuations that directly impact the cost of electricity and contribute to climate change. The Bahamas, with a vast coastline and access to ocean currents, could potentially explore tidal energy as a renewable energy source (Bethel et al. 2021), especially devices operating at less energetic flows (Encarnacion et al. 2019; Kaddoura et al. 2020). However, the specific suitability of tidal energy in the Bahamas would require detailed assessments and studies on:

- **Tidal currents:** Examining the local tidal current patterns, including the amplitude (tidal range) and frequency of tides, is crucial. Areas with larger tidal ranges typically offer more significant energy potential.
- **Coastal geography:** The Bahamas' coastal geography needs to be assessed, including the presence of suitable locations for tidal energy devices and cable landfalls to connect to local power grids.

Table 10.1. Baseline assessment requirements for the Clarence Strait tidal energy project and tropical tidal test center in Australia.

Receptors	Baseline assessment requirements
Marine vertebrates	• Extent and behavior of vertebrate marine species in and around project area
Marine mammals	• Assess physical interaction risk of tidal turbines • Understand acoustic interference and impact of device noise
Invertebrates	• Impacts of cables on benthic habitat
Terrestrial fauna and flora	• Describe and map native terrestrial and inter-tidal flora and fauna
Physical environment	• Bathymetry of turbine site and cable route to identify any seabed features of significance • Impacts of gravity base on seabed • Water quality of marine waters and spatiotemporal variations • Maps of regional distribution of species' suitable habitat and of habitat areas to be disturbed • Soil/sediment types and land units within the onshore project footprint
Human dimensions	• Describe floral and faunal species and biological communities of local, regional, and national significance • Describe the existing and projected maritime traffic use • Describe the isolated danger or safety zones required to mark and protect project assets • Identify archaeological/heritage artifacts of importance and vulnerability of features identified • Understand cultural impacts • Detail all chemicals to be stored and/or used on site

- **Environmental impact:** Conducting EIAs is essential to understand the potential effects of tidal energy projects on marine ecosystems, including fish and other aquatic life.
- **Infrastructure:** The availability of infrastructure, such as electrical grids and transmission lines, is vital for connecting tidal energy generation facilities to the electricity grid.
- **Economic viability:** Analyzing the cost-effectiveness of tidal energy projects and considering government incentives and policies for renewable energy development is crucial.

The Sharktunes project in the Bahamas aimed to study the response of large predatory fish to underwater noise from tidal energy devices to assess potential effects on, and if necessary, mitigation approaches to, these ecologically important species. This project is led by Uppsala University, Octopus Ink Research & Analysis, Chalmers University of Technology, and Swedish University of Agricultural Sciences. The tidal energy device studied for this project was the Minesto tidal kite. The underwater noise emitted from the tidal energy device included low frequency components which may hypothetically attract (or repel) species such as sharks and other large marine predators. All playbacks used in the study were broadcasted at realistic levels for a tidal kite, by far lower than those known to cause direct physiological injury for nearby individuals of fish or marine mammal species (U.S. Department of Commerce 2018). Two underwater noise profiles were emitted with an underwater speaker during a four-week field campaign in several locations in the vicinity of Cape Eleuthera (west side of Eleuthera), on the west side of the Bahamas (Figures 10.5, 10.6). The two noise profiles corresponded to the noise emitted by a prototype-size tidal kite (small tidal kite) and a full-scale tidal kite (big tidal kite). Shark behavior was recorded with stereo video cameras facing in two directions (two cameras vertically down, two cameras horizontally). Playbacks were emitted for 15 minutes and included sound profiles known to attract sharks (e.g., low frequency pulsed sound and helicopter sound), and sound profiles known to be a deterrent (e.g., sound of distant lightning strikes) (Chapuis et al. 2019).

As of 2024, the project is ongoing and final analyses remain to be completed. Preliminary results showed that Caribbean reef shark (*Carcharhinus perezii*), nurse shark (*Ginglymostoma cirratum*), bull shark (*Carcharhinus leu-*

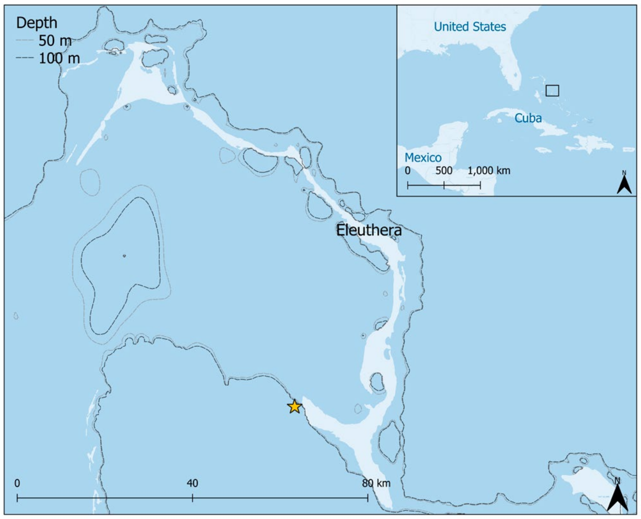


Figure 10.5. Map of the Sharktunes project location (yellow star) in Eleuthera, the Bahamas.

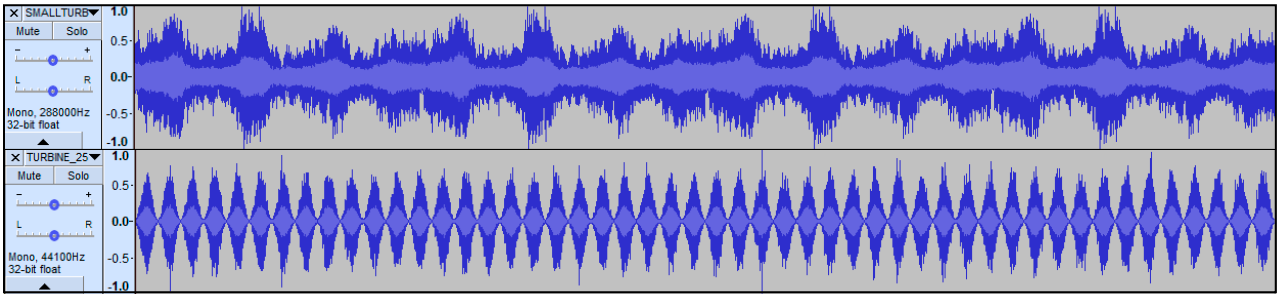


Figure 10.6. Noise profiles emitted in the marine environment using an underwater speaker to study the behavior of sharks in the Bahamas. Two noise profiles were used, corresponding to those emitted by a small tidal kite (top) and a big tidal kite (bottom).

cas), and great hammerhead shark (*Sphyrna mokarran*) were present during the field campaign (Figure 10.7). Caribbean reef, nurse, and bull sharks were not attracted to noise similar to a tidal kite, but seemed to avoid it, although habituation seemed to occur over time. Unlike the other species, bull sharks seemed attracted to the low frequency pulse noise, although the attractiveness of the noise dissipated with time, probably due to habituation. Finally, sudden loud noise startled the sharks, but the effect wore off rapidly. From these preliminary results, underwater noise effects from a tidal kite on sharks are likely low, but more studies are needed to better understand shark behavior around a real device.

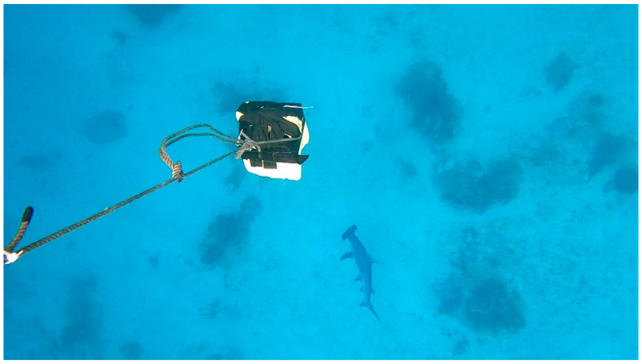


Figure 10.7. Picture of a great hammerhead shark swimming under the stereo video camera during recording.

OTEC IN MEXICO

Mexico is located on the border of two biogeographic regions (Nearctic and Neotropical), which contributes to the existence of a variety of climates and ecosystems, providing Mexico with great biodiversity (Koleff et al. 2018). Its long coastline and access to the Caribbean Sea, Gulf of Mexico, and Pacific Ocean provide heterogeneous conditions that offer a variety of marine resources for MRE exploitation (Hernández-Fontes et al. 2019).

Because of Mexico's great biodiversity, natural areas have been protected and zoning programs established by the National Commission for Natural Protected Areas for the protection of representative ecosystems, flora and fauna, natural resources, and environmental services, where extractive activities are restricted. Therefore, government and federal organizations must be involved in the development of any MRE projects, particularly during stakeholder engagement, as many of these protected areas are located along the coastline and co-occur with potential MRE sites (Hernández-Fontes et al. 2019), some of which are biodiversity hotspots (MacGregor-Fors et al. 2022; Myers et al. 2000). Although there have been few MRE projects off Mexico, research on the environmental interactions suggests potential effects on coastal habitats, such as mangroves, seagrass beds, and coastal lagoons, and on marine animals, such as sea turtles, migratory birds, endangered/threatened species (mostly marine mammals), and endemic fish species (Carrera Chan et al. 2020; Marin-Coria et al. 2021; Rivera et al. 2020; Wojtarowski et al. 2021).

Among the various MRE resources present off Mexico, OTEC has high potential. Suitable bathymetry and temperature differential for OTEC are found along both the Pacific and Caribbean Sea coastlines (Garduño-Ruiz et al. 2021). Although there are significant OTEC resources off Mexico, environmental concerns have slowed down the development of projects. Environmental effects were investigated at a theoretical location for an open-cycle OTEC plant on the west coast of Cozumel Island, Quintana Roo (Carrera Chan et al. 2020) (Figure 10.8). The significance of relevant environmental effects (positive or negative) and their magnitude associated with the presence of an OTEC plant were assessed. The four most significant negative effects identified were: dragging nutrients to the surface, redistribution of ocean water bodies, impact by organic antifouling chemicals, and brine discharge. OTEC projects could be developed around Cozumel Island if measures to minimize environmental effects are taken, such as avoiding mangrove habitat and protected natural areas. Other MRE technologies such as ocean current turbines are being considered in the region and environmental monitoring is under development.

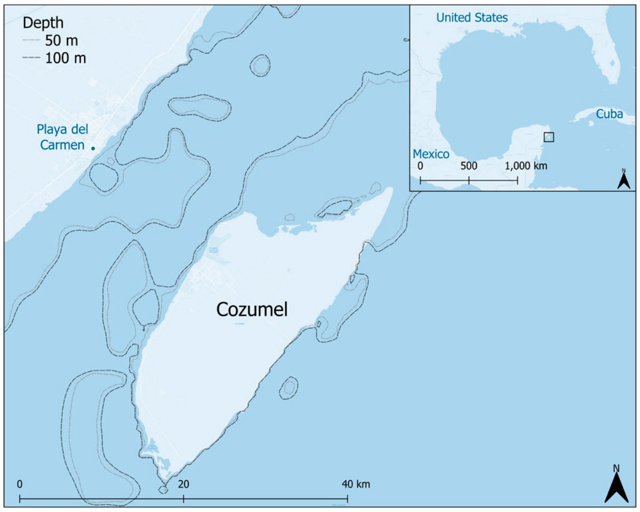


Figure 10.8. Map of Cozumel Island, Mexico.

10.5. RESEARCH NEEDS AND KNOWLEDGE GAPS

Tropical and subtropical marine ecosystems are composed of diverse habitats and complex ecological interactions spanning from the shoreline to the open ocean (Dahlgren & Marr 2004). These ecosystems face unprecedented anthropogenic threats and are vulnerable to environmental variations (Kenchington & Hutchings 2018). All countries considered to be megadiverse are in the tropical zone and there is a clear overlap between these biodiversity hotspots and MRE resources (Felix et al. 2019). These characteristics make tropical and subtropical ecosystems highly sensitive and increase their vulnerability to the cumulative effects of anthropogenic activities at sea, including MRE development.

When considering the development of MRE in these ecosystems, there is a lack of scientific information about the possible environmental effects, as compared to temperate regions. This lack of scientific information is largely due to the scarcity of MRE projects deployed in these regions so far. The slow development of the MRE industry in tropical and subtropical regions is generally linked to the lack of investment from government entities and to environmental and social constraints. Environmental regulations, marine spatial planning, industry roadmaps, guidance for developers, and standardization around EIA of MRE projects are generally lacking. In Latin American countries, there are few environmental or ecosystem characterizations and baseline data available for most of the coastline. Instead, environmental studies are typically conducted locally, are not conducted on a seasonal basis, and often the results are not well disseminated or made publicly available. The lack of long-term baseline data prevents a comprehensive understanding of the natural variations of ecosystems, which is needed to evaluate the potential effects of MRE projects (Mendoza et al. 2019). Similarly in Asia, because of the very early stage of MRE development there, knowledge and expertise about potential environmental effects are very limited and primarily built on other existing coastal and offshore activities such as fishing, aquaculture, and oil and gas. In Japan, the EIA law was implemented in 1999 (Environmental Impact Assessment Act 1997) and is commonly used to assess the environmental effects of diverse offshore activities, but it does not include guidance or laws on MRE.

To better understand the potential effects of MRE development on habitats, species, ecosystems, and communities in tropical and subtropical countries with suitable MRE resources, it is essential to establish and enable early stage projects, around which research and monitoring can be undertaken. This includes single device deployments and where suitable, small arrays. To fill knowledge gaps on the environmental effects of MRE in tropical and subtropical ecosystems, studies need to go beyond the framework of stressor-receptor interactions that is being used in temperate regions. Except for interactions related to OTEC technologies that can only be deployed in tropical and subtropical regions, there are no interactions entirely specific to the tropical and subtropical regions; differences lie in the species and habitats that are potentially impacted. Therefore, considering the whole ecosystem and the linkages between species is key (Hammar & Gullström 2011). To evaluate the potential effects of a salinity gradient energy project in Mexico, Wojtarowski et al. (2021) focused on describing the biogeochemical characteristics of the coastal lagoon ecosystem, the associated mangrove habitat, and the threatened and keystone species inhabiting the ecosystem. This approach enabled researchers to consider the structure and function of the ecosystems and the associated biodiversity (Martínez et al. 2021). Identifying priority and vulnerable habitats as well as monitoring and mitigating the long-term effects on nearby tropical ecosystems and migratory tropical species are key to sustainably advancing the industry. Extreme events (e.g., hurricanes, typhoons, tsunamis) are common in tropical and subtropical regions and their frequency and intensity are increasing with climate change (Balaguru et al. 2023; Cha et al. 2020); adapting MRE technologies to the environment and these extreme events is needed.

Social perception also plays a crucial role across tropical and subtropical regions and can either enable or hinder the development of MRE projects (Martinez & Komendantova 2020; Ramachandran et al. 2020). Coastal and island communities are observant and participative and can strongly influence the ultimate success or failure of a project. Project slowdowns or cancellations can happen either as a result of insufficient information on potential interactions of such projects with the surrounding environment or due to a negative perception of these industries in general (e.g., Clarence Strait tidal energy project in Australia). Social issues are heterogeneous within a country and a better understanding of concerns and potential social effects within a specific region is needed. The lack of knowledge on local social concerns would benefit from strong community involvement from the inception of an MRE project. Educating stakeholders on MRE in general and environmental and socioeconomic effects in particular will also benefit the MRE industry as awareness and education are key to community acceptance (Bonnevie et al. 2019; Ramachandran et al. 2020). More research is needed to better understand how the energy, financial, and social benefits of MRE can reach the nearby residents and businesses in a specific region (Hernández-Fontes et al. 2020; Lyons et al. 2023).

10.6. RECOMMENDATIONS

While access to research and development funding is often more limited in tropical and subtropical regions, baseline environmental research will help address many concerns for environmentally protected marine areas that may include endangered or threatened species, coupled with socioeconomic research that will improve understanding of the potential effects on local communities. Several recent studies have combined the investigation of both environmental and social effects to select sites for MRE projects in Mexico for salinity gradients (Wojtarowski et al. 2021), wave energy, current energy, and OTEC (Hernández-Fontes et al. 2020); and in China (Zhang et al. 2019) and Colombia (Osorio et al. 2016) for OTEC.

Recommendations for advancing the knowledge of the environmental effects of MRE in tropical and subtropical ecosystems include the following:

- Establishing collaborations and partnerships between industry, government, academia, and communities, to enable research around early stage MRE projects;
- Establishing a list of priority research questions on a regional or national basis;
- Combining monitoring and modeling studies to understand the natural variations of the environment;
- Applying a system-level effects approach to assess the cumulative effects of MRE with other anthropogenic activities at sea; and
- Establishing clear pathways for data transfer and knowledge sharing from projects in other parts of the world, including opportunities for technology transfer where appropriate.

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Suggested citation:

Garavelli, L., Hemery, L. G., Farr, H., Apolonia, M., Haywood, Z., Alamillo-Paredes, A., Bender, A. 2024. Potential Environmental Effects of Marine Renewable Energy in Tropical and Subtropical Ecosystems. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 252-271). doi:10.2172/2438599

Section F

LOOKING AHEAD

CHAPTER 11.0
SUMMARY AND PATH FORWARD

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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Suggested citation:

Copping, A. E. 2024. Summary and Path Forward. In L. Garavelli, A. E. Copping, L. G. Hemery, and M. C. Freeman (Eds.), OES-Environmental 2024 State of the Science report: Environmental Effects of Marine Renewable Energy Development Around the World. Report for Ocean Energy Systems (OES). (pp. 272-281). doi:10.2172/2438600

TECHNICAL GLOSSARY

Active acoustics: Technique of purposefully producing sound to receive signals (reflections) from animals in the water column.

Adaptive management: An iterative process to adjust methods and decisions based on growing information from monitoring data.

Alternating current (AC): Electric current which periodically reverses direction.

Ambient noise: Background noise in the environment and distinct from the noise emitted by a marine energy device or monitoring equipment.

Benthic: Related to animals inhabiting the bottom of the water column.

Biofouling: Accumulation of microorganisms, plants, algae, or small animals on underwater structures.

Collision: When an animal contacts with the moving parts (often a blade) of a turbine.

Consenting/permitting: To allow, or permit, the development of a project based on regulatory or legislative requirements.

Cumulative effects: Changes to the environment caused by the combination of past, present, and future human activities and natural processes.

Data transferability: The process of making information and datasets more accessible and more efficient for direct application to other locations and projects.

Direct current (DC): Electric current that flows in one direction.

Displacement: The outcome of one of three mechanisms (i.e., attraction, avoidance, and exclusion) triggered by a receptor's response to one or more stressors acting as a disturbance, with various consequences at the individual through to population levels.

Ecosystem processes: The various biological, chemical, and physical interactions that occur within an ecological system.

Electromagnetic fields (EMF): Occur naturally in the environment and consist of electric fields (E-fields), measured in volts per meter (V/m), and magnetic fields (B-fields), measured in Tesla (T).

Entanglement: Occurs when an animal becomes directly entangled with mooring lines or cables.

Marine renewable energy: Involves the generation of energy from the movement of seawater including tides, waves, and persistent ocean currents, as well as from the gradients of temperature and salinity in the oceans. For the purpose of this report, marine renewable energy does not include offshore wind or tidal barrages.

Marine Spatial Planning: An approach to analyzing and managing marine activities to minimize conflicts and balance environmental, social, and economic objectives.

Ocean current energy: Capturing energy from ocean currents.

Ocean thermal energy conversion conversion (OTEC): Capturing energy using temperature gradients across water depths.

Passive acoustics: Technique of listening to the sounds produced by animals in the water column.

Pelagic: Related to animals inhabiting the water column of the open ocean.

Receptor: Animal, habitat, or ecosystem processes susceptible to be harmed or stressed.

Riverine energy: Capturing energy from river currents.

Salinity gradient energy: Capturing energy from salinity gradients where freshwater meets seawater.

Stakeholders: Anyone (individuals or groups) with an interest or concern in a specific issue, particularly those who can affect or be affected by its outcomes.

Stressor: Parts of a device or result of a device's functioning that may cause harm or stress to an animal, habitat, or ecosystem processes.

Tidal energy: Capturing energy from tidal fluctuations.

Wave energy: Capturing energy from waves.

PHOTO CREDITS

OES-Environmental 2024 State of the Science report and executive summary available at:
https://tethys.pnnl.gov/publications/state-of-the-science-2024

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