ANNEX IV

2016

State of the Science Report

ENVIRONMENTAL EFFECTS OF MARINE RENEWABLE ENERGY DEVELOPMENT AROUND THE WORLD

U.S. DEPARTMENT OF ENERGY
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APRIL 2016

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AVAILABILITY OF REPORT

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ACRONYMS AND ABBREVIATIONS

1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
AC	alternating current
ADCP	acoustic Doppler current profiler
ADV	acoustic Doppler velocimeter
AMETS	Atlantic Marine Energy Test Site
AMREP	Areas of Marine Renewable Energy Priority
BACI	Before-After-Control-Impact
BIMEP	Biscay Marine Energy Platform
BioPA	Biological Performance assessment
BOEM	Bureau of Ocean Energy Management
BRI	Boschma Research Incorporated
CBTEP	Cobscook Bay Tidal Energy Project
CCDR	Coordination Committee on Regional Development
CFD	computational fluid dynamics
CGS	centimeter–gram–second
cm	centimeter(s)
CMSP	Coastal and Marine Spatial Planning
CORER	Centre for Ocean Renewable Energy Resources
CPT	Colombia Power Technologies
CPZ	Cable Protection Zone
CRM	collision risk modeling
CTD	conductivity-temperature-depth
dB	decibel(s)
dB rms	decibel(s) root mean square
DIDSON	Dual-Frequency Identification Sonar
DNMS	drifting noise measurement system
DO	dissolved oxygen
DOE	U.S. Department of Energy
EEZ	Exclusive Economic Zone
EIA	Environmental Impact Assessment
EIS	Environmental Impact Study
ELAM	Eulerian-Lagrangian-Agent Model
EMEC	European Marine Energy Centre
EMF	electromagnetic field
EMP	Environmental Monitoring Plan
EMV	Electromagnetic Velocity Meter
EPRI	Electric Power Research Institute
ES	Environmental Statement
ETPM	Exposure Time Population Model
EU	European Union
EVE	Ente Vasco de la Energía (Basques Energy Board)
EWTEC	European Wave and Tidal Energy Conference
FAD	fish aggregating device
FERC	Federal Energy Regulatory Commission
FORCE	Fundy Ocean Research Center for Energy
FVCOM	Finite Volume Coastal Ocean Model
g	gram(s)
GIS	geographic information system
HGE	Hydro Green Energy
HPR	heading, pitch, and roll
hr	hour(s)
Hz	hertz
HVDC	high-voltage direct current
ICNF	Instituto de Conservação da Natureza e das Floresta
IDEA	Instituto para la Diversificación y Ahorro de la Energía
IEA	International Energy Agency
iE-field	induced-electric field
IHA	Incidental Harassment Authorization
in.	inch(es)
INSPIRE	Infrastructure for Spatial Information in Europe
kA	kiloampere(s)
kHz	kilohertz
km	kilometer(s)
kV	kilovolt(s)
LLC	Limited Liability Company
LOMA	Large Ocean Management Area
m	meter(s)
MaREI	Marine Renewable Energy Ireland
MCT	Marine Current Turbines
MERMA	Ministry of the Environment, Rural and Marine Affairs
MFZ	marine functional zoning
MHK	marine and hydrokinetic

~~MITT~~	~~Ministry of Industry, Tourism and Trade~~
mm	millimeter(s)
MMO	Marine Management Organisation
MRE	marine renewable energy
MREA	Marine Renewable Electricity Area
m/s	meter(s) per second
MSFD	Marine Strategy Framework Directive
MS-LOT	Marine Scotland-Licensing Operations Team
mT	millitesla
mV	millivolt(s)
MW	megawatt(s)

NGO	non-governmental organization
NI	Northern Ireland
NIOMR	Nigerian Institute for Oceanography and Marine Research
NNMREC	Northwest National Marine Renewable Energy Center
NOAA	National Oceanic and Atmospheric Administration

nT	nanotesla
nV	nanovolt(s)
NZCPS	New Zealand Coastal Policy Statement

OES	Ocean Energy Systems Initiative
OREDP	Offshore Renewable Energy Development Plan
ORNL	Oak Ridge National Laboratory
ORPC	Ocean Renewable Power Company
OTEC	Ocean Thermal Energy Conversion

µPa	micropascal(s)
PAM	Passive Acoustic Monitoring
PBR	Potential Biological Removal
PCoD	Population Consequences of Disturbance
PNNL	Pacific Northwest National Laboratory
PoE	Pathways of Effect
PTS	permanent threshold shift
PVA	population viability analysis

RD&D	research, development, and demonstration
ReDAPT	Reliable Data Acquisition Platform for Testing
RITE	Roosevelt Island Tidal Energy
RMA	Resource Management Act
rms	root mean square
RPB	Regional Planning Body
RPM	rotations per minute

s	second(s)
SAC	Special Area of Conservation
SAMP	Special Area Management Plan
SAMS	Scottish Association for Marine Science
SCANS	Small Cetaceans in the European Atlantic and North Sea
SEA	Strategic Environmental Assessment
SECOA	Social, Economic, and Cultural Overview and Assessment
SEL	sound exposure level
SELcum	cumulative SEL
SELSS	single strike SEL
SBT	split-beam transducer
SI	International System of Units
SMRU	Sea Mammal Research Unit
SNL	Sandia National Laboratories
SOA	State Oceanic Administration
SPA	Special Protection Area
SPL	sound pressure level
SPLpeak	peak SPL
SPLpeak-peak	peak-to-peak SPL
SRSL	SAMS Research Services Ltd
SSE	Strategic Scoping Exercise
SURGE	Simple Underwater Renewable Generation of Energy (project)
SwAM	Swedish Agency for Marine and Water Management
SWAN	Simulating WAves Nearshore

µT	microtesla
T	tesla
TDR	time-depth recorder
TEC	Tidal Energy Converter
TEL	Tidal Energy Ltd
TGU	turbine generator unit

UK	United Kingdom
US	United States
UTM	Universal Transverse Mercator
µV	microvolt(s)
VAMS	Vessel-mounted Aimable Monitoring System
V/m	volt(s) per meter

WEA	Wind Energy Areas
WEC	wave energy converter

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Executive Summary

This report summarizes the state of the science of interactions and effects of marine renewable energy (MRE) devices on the marine environment, the animals that live there, and the habitats that support them. This report serves an update and a complement to the 2013 Annex IV report that can be found at *http://tethys.pnnl.gov/publications/final-annex-iv-report-2013*.

Generating energy from the ocean includes the use of offshore wind turbines. This report considers only devices that generate energy from seawater. The MRE industry worldwide is still in the early stages of development, deployment, and commercialization. While MRE devices include those aimed at harvesting tides, waves, and ocean currents, as well as temperature and salinity differentials in seawater, the majority of environmental studies have focused on tidal turbines and wave energy converters (WECs), with some emphasis on ocean current and river turbines. This report considers turbines and WECs only.

This report was produced by the Annex IV Initiative, under the Ocean Energy Systems (OES) collaboration. Thirteen OES countries have joined together to assess the potential environmental effects of MRE development, and to learn collectively how to address potential effects that hamper siting and consenting/permitting of devices, to facilitate the establishment of the MRE industry.

The information gathered and analyzed for this report can help inform regulatory and research investigations of potential risks to marine animals and habitats from tidal and wave installations, and can assist MRE developers in developing engineering, siting, operational strategies, and monitoring options for projects that minimize encounters with marine animals and/or diminish the effects if such encounters occur. Used in conjunction with site-specific knowledge, the information from this report may simplify and shorten the time to permit (consent) deployment of single and multiple device arrays. The information brought together for analysis represents readily available, reliable information about environmental interactions with MRE devices; however, the analysis and conclusions drawn are not meant to take the place of site-specific analyses and studies, or to direct permitting (consenting) actions or siting considerations in specific locations.

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

In a new industry like MRE, there may be interactions between devices and marine animals or habitats that regulators or stakeholders perceive as risky. In many instances, this perception of risk is due to the high degree of uncertainty that results from a paucity of data collected in the ocean. However, the possibility of real risk to marine animals or habitats cannot be discounted; the lack of data continues to confound our ability to differentiate between real and perceived risks.

Ultimately, risk will be governed by a variety of factors that include attributes of a particular device (static or dynamic), the type of device (wave or tidal), and the spatial scale of a particular installation (single device or arrays). As the MRE industry continues to develop, it is important to acknowledge all the potential mechanisms of harm these technologies may pose to the marine environment, although many of the perceived risks are likely to be small and easily avoided or mitigated. Additional strategic research investments will likely help to minimize uncertainty and elucidate actual risk. Most interactions and associated risks from single devices are unlikely to harm the marine environment; as larger arrays are deployed, additional monitoring and strategic research may be required to prepare for the commercial development of the industry.

Studies to date have shown that most of the perceived risk to animals from MRE devices is due to uncertainty about the interactions because of the lack of definitive data, and continue to present challenges to permitting/consenting of commercial-scale development. As more definitive data are collected, it is possible that some real risks to marine animals and habitats will remain and continue to present challenges to permitting/consenting of commercial-scale development.

BENEFITS OF MARINE ENERGY

The push for MRE development around the world stems from interest in developing locally derived secure energy sources that have the potential to combat the effects of climate change such as ocean acidification and increasing ocean temperatures. Deleterious effects of climate change are already affecting many marine and coastal resources, and will continue to affect the health, reproduction capabilities, and biodiversity of populations of fish, shellfish, marine mammals, and birds, and other living organisms. Similarly, climate change effects will erode the beneficial human uses we derive from the harvest and aquaculture of seafood organisms, as well as degrade coastal habitats that provide erosion and storm protection. Although laws and regulations in some countries do not explicitly allow for calculation of these beneficial uses by MRE devices as offsets for potential deleterious effects, the net benefits of MRE generation should be viewed as combatting climate change.

COLLISION RISK FOR ANIMALS AROUND TIDAL TURBINES

The potential for marine animals to collide with the moving parts of tidal devices is a primary concern for consenting/permitting and licensing of tidal developments. Where proposed tidal energy projects overlap with the habitat of protected species there are concerns that collisions could lead to injury and mortality of individuals, and possibly affect the long-term status of the population.

Marine mammals, fish, and seabirds are of greatest concern for collision, however no collisions have been observed around single turbines or small arrays to date. Studies have focused on observing the behavior of animals around turbines as a way to understand how mechanisms leading to collisions might occur. However, observing collision and animal behavior around turbines is hampered by a lack of appropriate instruments and challenging conditions for underwater observations using acoustic or optical instruments. Modeling efforts to estimate potential consequences of collisions with turbines provide some insight for worst-case scenarios, but need validation from the field. Researchers are also examining animal behavior around turbines including evasion, avoidance, and attraction; direct observation of animal movements and behavior in the vicinity of devices is needed to inform evaluations of risk and impacts, and to answer stakeholder and regulator questions.

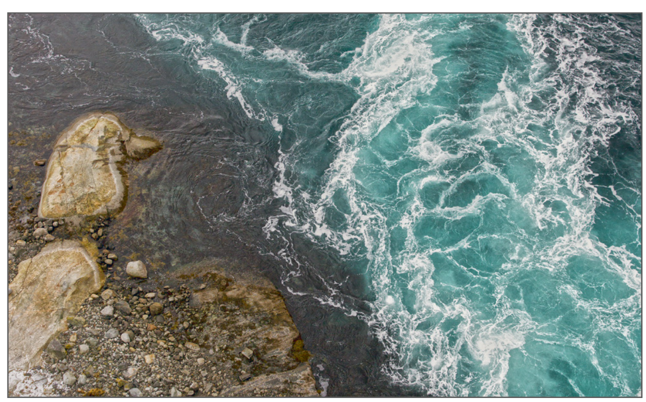
RISK TO MARINE ANIMALS FROM UNDERWATER SOUND GENERATED BY WAVE AND TIDAL DEVICES

Animals use sound in marine environments for communication, social interaction, orientation, predation, and evasion. The extent to which marine animals detect and emit sound varies by frequency and amplitude. The addition of anthropogenic noise sources from operational wave and tidal devices may induce behavioral changes in marine animals. In addition to behavioral changes, the addition of noise may, in some cases result in injury. Physical impacts may include temporary or permanent reduction in hearing ability, damage to non-auditory tissues, irregular gas bubble formation in the tissues of fish and marine mammals, and neurotrauma. Behavioral changes may also occur, such as avoidance of or attraction to the source, as well as masking—interference with communication, navigation, and detection of prey. To date, there have been no observations of operational noise from MRE devices affecting marine animals.

Measuring the sound from an operational WEC or tidal turbine is becoming more routine, although measuring low-frequency sounds that may be in the hearing range of large whales continues to be challenging. Observations of animals reacting to those sounds are more difficult to obtain. More information is needed to determine whether physical injury and behavioral changes caused by installation noise will be harmful. Most sound measurements from MRE devices have been gathered for single devices; although we can bound the likely acoustic outputs from the cumulative impacts of arrays, few field measurements have been made to date.

CHANGES IN PHYSICAL SYSTEMS: ENERGY REMOVAL AND CHANGES IN FLOW

In marine environments, physical systems act as drivers for the sustainability and health of organisms. The installation of MRE devices may affect the system by changing natural flow patterns around devices, which can alter sediment distribution and transport. In addition, energy removal may change the operation of a waterbody. A small number of MRE devices will not create measurable changes, but large commercial arrays might alter the system over time.

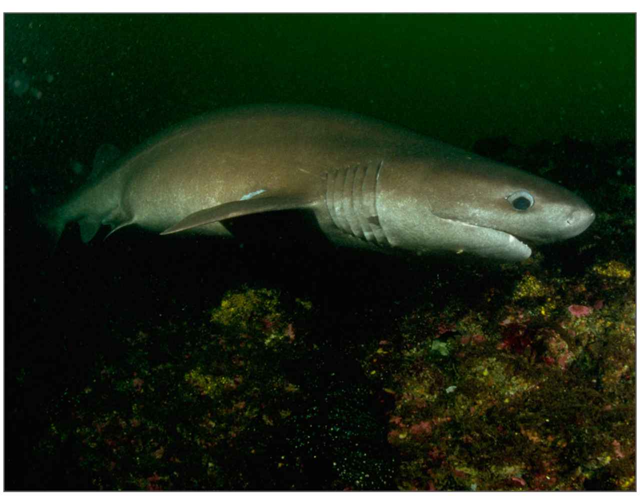


There are few field studies of energy removal and changes in flow caused by MRE devices. Many numerical models have been developed and applied to the problem, although most models have focused on optimizing power generation. Fewer models have focused on environmental concerns like changes in water circulation, sediment transport, and water quality. All the models that examine potential effects on the environment need field data to validate the conclusions, which continues to limit their use.

EFFECTS OF EMF ON MARINE ANIMALS FROM ELECTRICAL CABLES AND MARINE ENERGY DEVICES

Electromagnetic fields (EMFs) occur naturally in the marine environment, while anthropogenic activities may create altered or additional sources of EMF, including those from MRE export cables. Cables are commonly buried or lying on the seabed, while inter-device cables may be suspended in the water column.

Evaluating the emissions from cables and energized devices requires measurements of the magnetic field and the induced electrical field. Laboratory and field studies examine the effects these emissions may have on marine animals, including certain electro- and magneto-sensitive species of fish, invertebrates, and possibly sea turtles. Most studies have focused on the behavioral responses by animals to the EMFs including the potential for a barrier effect that might keep animals from important habitats, slowing of growth or development in larval animals, and behavior changes that might limit feeding. To date there has been no evidence to show that EMFs at the levels expected from MRE devices will cause an effect (whether negative or positive) on any species.

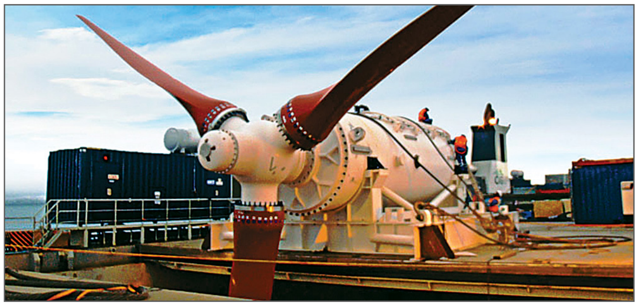


CHANGES TO HABITATS CAUSED BY MRE DEVICES: BENTHIC HABITATS AND REEFING PATTERNS

The installation of MRE devices alters benthic (bottom) habitats by the addition of gravity foundations, piles, or anchors, as well as the sweep of mooring lines, cables, and mechanical moving parts. Similarly, the presence of MRE devices on the seafloor or suspended in the water column may attract fish and benthic organisms, allowing them to reef around the device, which may change their behavior, location, and perhaps have a population effect.

Most evidence of changes in benthic habitats are related to offshore wind installations, which may provide some insight into changes expected from MRE devices. Changes are not expected to be widespread or to affect benthic habitats differently than other marine industries that place structures in new areas of the ocean.

Effects that MRE devices have on reefing fish are not known, and are expected to be very similar to those of other marine industries, including the installation of artificial reefs, which have not been shown to have deleterious effects on fish populations. It is possible that MRE devices will increase the density of certain fish species locally.



MARINE SPATIAL PLANNING AND MARINE RENEWABLE ENERGY

Marine spatial planning (MSP) involves an approach to planning and managing sea uses and users to support sustainable development of marine areas. The rationale for MSP is to provide a stable and transparent planning system for maritime activities and users within agreed environmental limits to ensure marine ecosystems and their biodiversity remain healthy, working across multiple sectors.

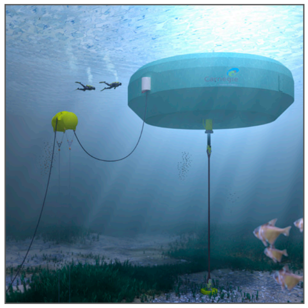
Annex IV representatives were surveyed to determine the extent to which MSP processes exist in their countries. Several nations have formal MSP processes in place, others have coastal management plans that embody some of the principles of MSP, and several have no MSP in place.

CASE STUDIES THAT EXAMINE SITING AND PERMITTING OF MRE DEVICES

The consenting process is still regarded as a barrier for the sector to scale up and become cost-competitive with other forms of electricity generation. Uncertainties about the application of environmental legislation can prolong consenting processes, adding costs, delays, and significant uncertainty. Four case studies are presented: two tidal devices (ORPC TidGen® Power System, installed in the United States; MCT SeaGen technology installed in Northern Ireland); one WEC (WaveRoller, installed in Portugal); and one designated test site (BIMEP, in the Basque Country, Spain). The intent of the case studies is to provide insight into the various complexities associated with siting and consenting MRE projects and test sites.

Time-consuming procedures—linked to uncertainty about project impacts and the need to consult with numerous stakeholders before reaching a permitting decision—appear to be the main obstacles to consenting of ocean energy projects. Dedicated legislation does not exist or is not clear in the jurisdictions examined. However, in some cases, regulators are willing to collaborate with developers. The consenting process and the environmental monitoring requirements are costly.

Outreach efforts, perceived as being critical to working with stakeholders, promote public awareness and understanding about MRE technologies. There is also a need to improve or adapt existing legislation and guidance to facilitate licensing of MRE farms. These efforts are already under way in some nations.



SUMMARY AND PATH FORWARD FOR MARINE ENERGY MONITORING AND RESEARCH

The 2016 State of the Science report summarizes and places in context information about the environmental effects of MRE development, to the extent that the information is publicly available. As single device deployments continue and development of the first commercial arrays is on the horizon, several critical interactions between MRE devices and marine animals continue to concern regulators and stakeholders: collision, underwater sound, and electromagnetic fields.

The risks associated with many interactions continue to be driven by uncertainty; these risks need to be better understood and managed, as they are for other established offshore industries. The interactions that are shown to not cause harm to the marine environment need to be "retired," allowing research and monitoring efforts to focus on the highest priority interactions. All of these risks can be parsed into three groups: 1) low-risk interactions that have been discounted or retired from ongoing monitoring; 2) interactions that have a high level of uncertainty and require further investigation; and 3) interactions that are known to be high risk to the marine environment and that will require mitigation through improved siting, improved design or operation of the devices, and perhaps an adaptive management approach, prior to scaling up to arrays. Eventually all interactions should be retired or mitigated through a range of actions including avoidance and minimization.

The interactions among marine animals/habitats and MRE devices that the regulatory community feels are important can be approached through three strategies:

- Certain interactions can be effectively monitored now with existing instruments, platforms, and technologies, although improvements in the instrumentation and data management could make monitoring more efficient.
- Other interactions require targeted strategic research efforts immediately in order to understand the risk of the interaction, and to decrease the costs and years of monitoring over the life of a project.
- There are no viable methods for monitoring certain interactions at this time; therefore strategic research investments are the only path forward.

Researchers, regulators, and developers have an opportunity to identify and hone strategic research investments that could inform the stressor-receptor interactions that are highly uncertain, allowing for streamlined pathways to siting and consenting/permitting, as well as lowering ongoing post-installation monitoring costs to levels that will move the industry forward. A framework for determining those strategic research investments is included in the report.

FOR MORE INFORMATION

Annex IV State of the Science full report and executive summary available at: *http://tethys.pnnl.gov/publications/state-of-the-science-2016*

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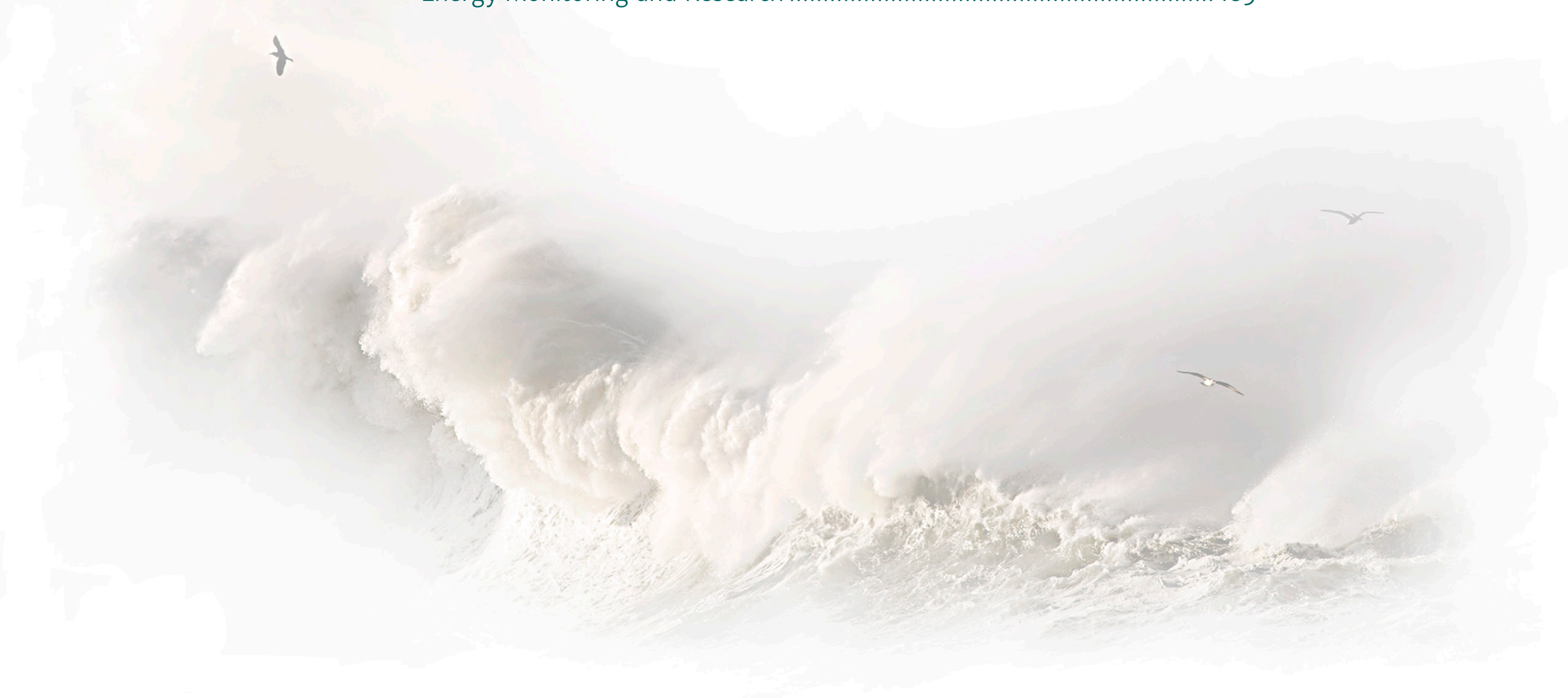
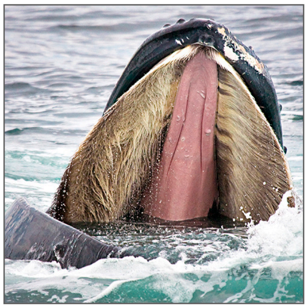


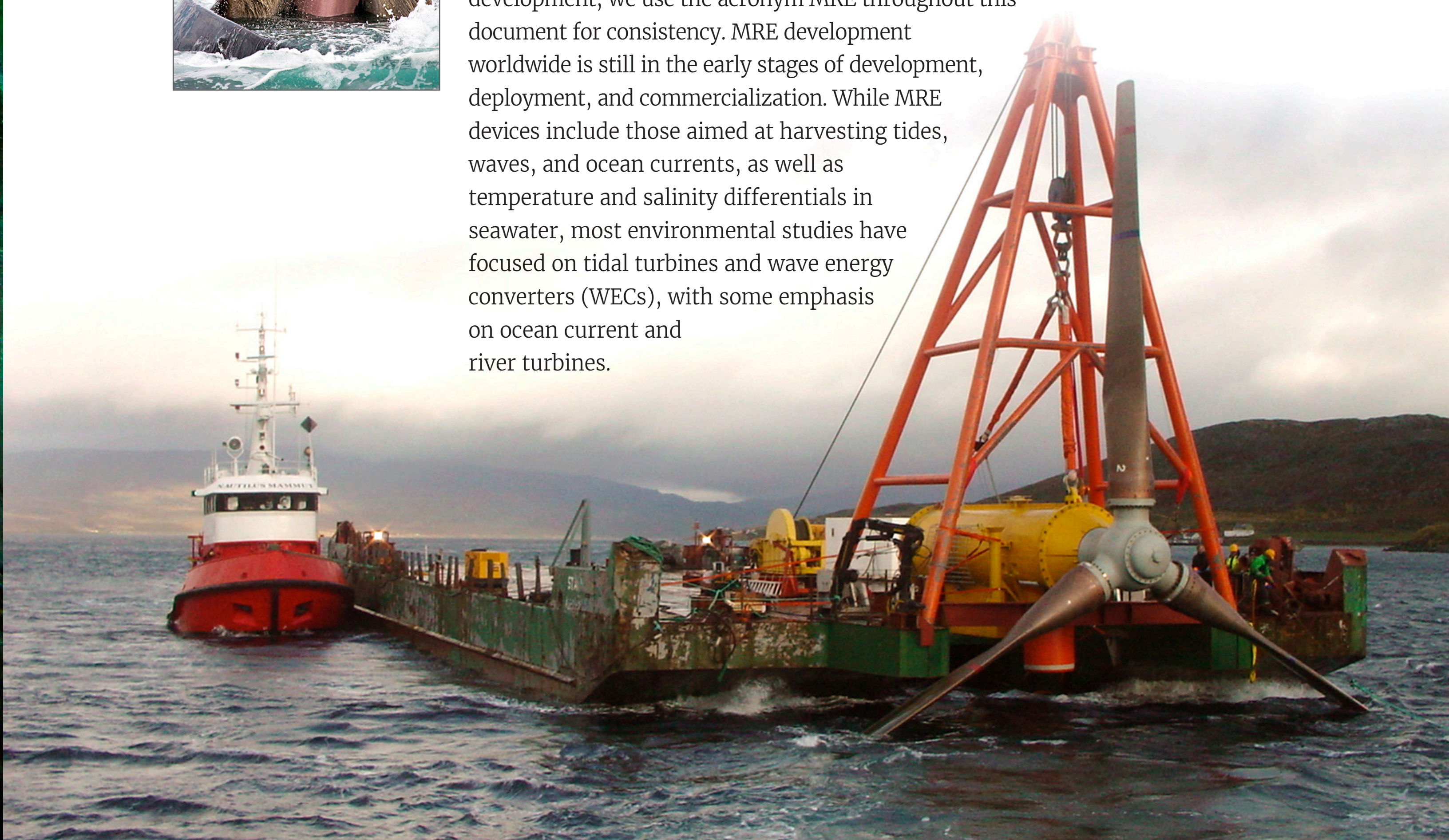
1.0 Introduction

Chapter author: A. Copping

This report summarizes the state of the science of interactions and effects of marine renewable energy (MRE) devices on the marine environment, the animals that live there, and the habitats that support them. This report serves an update and a complement to the 2013 Annex IV report that can be found at *http://tethys.pnnl.gov/publications/final-annex-iv-report-2013*.



Generating energy from the ocean includes the use of offshore wind turbines. This report considers only devices that generate energy from seawater. MRE development is also referred to as ocean energy development, or marine and hydrokinetic energy development; we use the acronym MRE throughout this document for consistency. MRE development worldwide is still in the early stages of development, deployment, and commercialization. While MRE devices include those aimed at harvesting tides, waves, and ocean currents, as well as temperature and salinity differentials in seawater, most environmental studies have focused on tidal turbines and wave energy converters (WECs), with some emphasis on ocean current and river turbines.



Power can also be generated by capturing the energy from the tidal range, using tidal barrages or tidal lagoons. Tidal barrages capture tidal energy by placing dams across estuaries or river mouths and allowing the outgoing and/or incoming tide to turn generators mounted in the dam for power production. Barrages are commonly considered to destroy the ecological function of the estuary or river mouth where they are constructed. Tidal lagoons are designed to impound a significant area of a coastal bay with a causeway or wall, funneling the outgoing and/or incoming tide through generators set in the wall. Tidal lagoons are under development in the UK and other parts of the world. The likely environmental effects of tidal lagoons have not yet been evaluated and will require investigation as this form of tidal energy development moves forward.

While offshore wind development also uses the resources of the ocean, this report does not include advancements or environmental effects of that technology, although in some cases, information gleaned from offshore wind farms may be used as surrogates for potential effects of MRE devices. In this report, MRE is used primarily to connote tidal and wave development.

1.1 BENEFITS OF MARINE ENERGY

Many countries are pursuing the development of broad portfolios of renewable energy sources to combat effects of climate change such ocean acidification and increasing ocean temperatures, as well as the need to acquire reliable safe sources of energy. For nations with coastal and ocean resources, the generation of energy from the ocean provides an attractive potential contribution to the renewable energy mix. Depending on the location and availability of energy-rich sites, tidal, wave or other marine energy forms may be exploited. In each location, a mix of marine animals and habitats must be considered in the development of this new industry, recognizing that many marine animal and bird populations are already under pressure from human activities such as fishing, coastal development, shipping, and resource extraction. It is also important to note that marine animal populations that draw the greatest scrutiny are themselves commonly at risk from the changing temperature and acidity of the oceans. Atlantic and Pacific salmon are important fisheries resources as well as vital food sources for many marine mammals, and are highly affected by changes in their land-based spawning grounds due to increased river and stream temperatures and changing precipitation patterns (Crozier and Hutchings 2014; Lawrence et al. 2014; Jonsson and Jonsson 2009). Planktonic organisms that support fish, sea turtles, and baleen whales are less able to reproduce in the increasingly acidic oceans, if they require calcium carbonate for life (Rossoll et al. 2012; Fabry et al. 2008). Changing wind and wave patterns due to storm frequency and duration are affecting the quality and aerial extent of submerged habitats in coastal and ocean areas (Doney et al. 2012).

While all MRE devices will alter the immediate location into which they are deployed to some extent, they may also provide alternative, often valuable, habitats that are in short supply. For example, for typical soft-bottom habitats on continental shelves and slopes, the addition of an anchor or foundation may provide a holdfast for encrusting organisms like barnacles or anchored plants like kelp that provide needed food and shelter for many young marine organisms (Langhamer and Wilhelmsson 2009). MRE devices may also act as artificial reefs, providing shelter and food sources for fish that reef around structures in the water, and potentially increase fisheries production (Powers et al. 2003).

MRE development will also have the effect of decreasing the need for large-scale marine transport of fossil fuels, hence reducing the risk of spills of petroleum products that are highly detrimental to marine organisms, birds, and habitats, in waterways and ocean basins.

While laws and regulations in many countries do not explicitly allow for calculation of these beneficial uses of MRE devices as offsets for potential deleterious effects, the net benefits of MRE generation should be viewed as combatting climate change. By generating power from low carbon sources such as MRE, we can directly mitigate climate change pressures that are placed on all living marine resources, as well as help to support other human uses such as fisheries, recreation, and waste disposal.

1.2
OCEAN ENERGY SYSTEMS

Launched in 2001[1], Ocean Energy Systems (OES) is an international, intergovernmental collaboration that operates within a Framework for International Technology Cooperation established by the International Energy Agency (IEA)[2] in Paris, France. The framework features multilateral technology initiatives that encourage technology-related research, development, and demonstration (RD&D) to support energy security, economic growth, and environmental protection. The Working Group for the OES Initiative advises the IEA Committee on Energy Research and Technology, which guides initiatives to shape work programs that address current energy issues.

Under the OES Initiative, countries are brought together to advance RD&D of conversion technologies to harness energy from all forms of ocean renewable resources—such as tides, waves, currents, temperature gradients (ocean thermal energy conversion and submarine geothermal energy), and salinity gradients for electricity generation, as well as for other uses, such as desalination—through international cooperation and information exchange. The collaboration consists of 23 member countries (as of April 2016), each of which is represented by a Contracting Party that nominates representatives to the OES Executive Committee, which is responsible for the OES work program.

Executive Committee participants are specialists from government departments, national energy agencies, research, or scientific bodies and academia.

The OES work program carried out by the Contracting Parties consists of RD&D, analysis, and information exchange related to ocean energy systems. Work is conducted on diverse research topics that are specified in "Annexes" to the Implementing Agreement. Each annex is managed by an Operating Agent, usually the member nation that proposes the initiative and undertakes a plan of activities.

1.3
ORIGINS AND INTENT OF ANNEX IV

The concept for the formation of this annex focused on the potential environmental impacts of ocean renewable energy was initiated by the United States and Canada in 2006. It responds to a need for information about the environmental effects described in the summary of the IEA's meeting on ocean energy systems held in Messina, Italy (the Messina report).[3] Following an experts' meeting in late 2007, the United States developed a proposal for the formalization of Annex IV, which was submitted and approved by the OES Executive Committee in 2008. The proposal stated the need to compile and disseminate information about the environmental effects of ocean renewable energy and to identify methods of monitoring for such effects. Annex IV was proposed to focus primarily on ocean wave, tidal, and current energy development, and was approved by the OES Executive Committee for an initial three-year phase in 2009. Seven nations (Canada, Ireland, Spain, Norway, New Zealand, South Korea, and the United States) participated in Annex IV through formalized commitments to the effort and the development of a work plan and budget for the project. The United States led the annex, with the U.S. Department of Energy (DOE) acting as the Operating Agent, in cooperation with other U.S. federal agencies (Federal Energy Regulatory Commission, Bureau of Ocean Energy Management [BOEM], and National Oceanic and Atmospheric Administration [NOAA]). As one of the DOE's national laboratories, Pacific Northwest National Laboratory (PNNL) implemented the project, with assistance from the Wave Energy Centre in Portugal and the University of Plymouth in the United Kingdom (UK).

A second phase of Annex IV was authorized by the OES Executive Committee in May 2013 for three additional years (2013 - 2016). Thirteen nations participated in Phase 2 (Canada, China, Ireland, Japan, Nigeria, Portugal, Spain, Sweden, Norway, New Zealand, South Africa, the United Kingdom, and the United States). The United States again led the annex, with DOE serving as the Operating Agent and U.S. federal partners (BOEM and NOAA). PNNL implemented Phase 2 of the annex with assistance from Aquatera Ltd. in the UK.

1. *http://www.ocean-energy-systems.org.*
2. *http://www.iea.org/.*
3. National Renewable Energy Laboratory (USA) and Natural Resources Canada (Canada). October 18, 2007. Potential Environmental Impacts of Ocean Energy Devices: Meeting Summary Report.

1.4
ANNEX IV ACTIVITIES

Annex IV has consisted of two 3-year phases. Phase 1 was active from 2010 through May 2013. Phase 2 commenced in May 2013 and will conclude in May 2016.

1.4.1
ANNEX IV PHASE 1

In 2009, the seven participating countries formalized commitments to the effort and developed a work plan and budget for the project. The work plan described a three-year effort to do the following:

- Compile information from monitoring and mitigation efforts conducted around deployed MRE devices and analogous marine technologies. This effort was further refined to include the collection of metadata on all tidal and wave deployments that provide insight into environmental effects, as well as research studies that focus on environmental interactions with MRE devices.
- Develop and populate a publicly accessible database to house this information. This database was integrated into *Tethys*, the online knowledge management system developed by PNNL.
- Organize two experts' workshops to inform the three-year Annex IV effort and provide feedback on Annex IV products. Two workshops were held in Dublin, Ireland, in September 2010 and in October 2012, with 58 and 52 researchers, from 8 and 9 nations, respectively, contributing to the direction, products, and oversight of Annex IV.
- Develop a report to characterize the environmental effects, identify successful monitoring and mitigation methods, and describe lessons learned and best practices derived from environmental monitoring and mitigation regimes. This report (Copping et al. 2013) was published by OES in January 2013.

Annex IV member nations appointed one of the DOE's national laboratories, PNNL, to lead the process of database development, data gathering, and analysis to support the objectives of Annex IV. Through a competitive solicitation, PNNL selected the Wave Energy Centre (Portugal) and the University of Plymouth (UK) as contractors to assist with data collection. PNNL also hired the Irish Marine Institute to organize and host the first experts' workshop; a report from this workshop is available at *http://tethys.pnnl.gov/publications/oes-ia-annex-iv-environmental-effects-marine-and-hydrokinetic-devices*.

In 2011, PNNL developed the framework for the Annex IV database using the existing structure for a knowledge management system already under development in the United States (known as *Tethys*), which was designed to accumulate and organize environmental information for marine energy and offshore wind development.

In 2012, Annex IV representatives gathered metadata on MRE projects and research studies. The metadata forms, in addition to other documents and reports in the database, were analyzed and used to develop three case studies, which provide a snapshot of the current research into and understanding of three types of potential environmental impacts of particular concern for MRE development. The case studies focused on: collision of marine animals with turbines; effects of underwater noise from marine energy devices on marine animals; and effects of energy removal and changes in flow in marine systems; and were documented in the Annex IV report from Phase 1 (Copping et al. 2013).

1.4.2
ANNEX IV PHASE 2

The workplan for Annex IV Phase 2 (2013-2016) built on the following tasks initiated during Phase 1:

- Compile information from baseline data collection and monitoring efforts around deployed MRE devices and analogous marine technologies, as well as related research studies on environmental effects. To date, there are 81 metadata forms on marine energy sites and 56 metadata descriptions of research studies on the environmental effects of MRE devices.
- Continue to populate the publicly accessible knowledge management system *Tethys* to house scientific information about the environmental effects of marine energy, as well as the metadata collected for MRE projects and research studies. To date there are 3152 documents (of which 1363 are peer reviewed) that address environmental effects of MRE development on *Tethys*. Documents are continually added to *Tethys* as they become available.

In addition, the focus of Phase 2 has created a commons for collaboration and engagement of Annex IV constituents, including researchers, device and project developers, regulators, and stakeholders. The commons brings together these key groups through online meetings and presentations, occasional in-person meetings and workshops, and maintains a robust list of connections to individuals, organizations, and data sources to ensure that the best information about environmental effects of MRE development is shared worldwide. Specific activities pursued during Annex IV Phase 2 include the following:

- Webinars featuring experts studying the environmental effects of MRE devices, held approximately four times a year, including topics such as:
  - instrumentation for monitoring around MRE devices;
  - interaction of marine mammals and seabirds around MRE devices;
  - tidal energy research in the Bay of Fundy;
  - effects of energy removal by devices on physical systems;
  - effects of electromagnetic fields on marine animals; and
  - environmental effects research at MRE test sites.

These and all previous webinars have been archived on *Tethys* at: *http://tethys.pnnl.gov/environmental-webinars?content=water.*

- Researchers have been brought together online through a series of expert forums to discuss technical questions that are hindering the process of siting and permitting MRE devices. Topics have included
  - analysis of acoustic data around MRE devices;
  - risk of collision of marine animals around MRE devices:
    - definitions and limits;
    - availability and uses of field data; and
    - models for evaluating risk.

Presentations and audio files of the forums are available on *Tethys* at *http://tethys.pnnl.gov/expert-forums*.

- A biweekly message, known as *Tethys Blast*, goes out to the broad Annex IV/*Tethys* community of more than 1,000 individuals, updating them on new material available on *Tethys*, and including pertinent news and events in marine energy development. *Tethys Blast* reminds the community of links to *Tethys* and allows Annex IV to disseminate key messages. All *Tethys Blasts* are archived on *Tethys* at *http://tethys.pnnl.gov/tethys-blasts*.
- Individuals with expertise in environmental effects research as well as those who choose to participate in Annex IV activities are listed in a Connections database on *Tethys* accessible to anyone with a *Tethys* account. Approximately 213 individuals are listed, as well as 1045 organizations engaged in marine energy effects, and tens of databases that have direct relevance to Annex IV studies. All the people, organizations, and databases can be found under the Connections tab *Tethys* (*http://tethys.pnnl.gov/connections*) for *Tethys* account holders.
- Annex IV partnered in an international conference on marine energy that helped raise the profile of Annex IV and OES, and where the presence of Annex IV improved the quality of the environmental approach to marine energy development. Annex IV partnered with the European Wave and Tidal Energy Conference (EWTEC) 2015, held in Nantes, France, September 6 through 11, 2015. EWTEC is the premier scientific and engineering conference on renewable marine energy. Annex IV involvement increased the number of environmental research papers to 28, which is a significant increase over environmental papers at previous EWTEC conferences. In addition, Annex IV hosted a workshop on the State of the Science report that detailed the findings of Annex IV efforts in Phase 2 and sought feedback on the report topics.
- The culmination of Phase 2 of Annex IV is the preparation of this document—the 2016 State of the Science report. This document builds on the 2013 Final Report for Phase 1 and reflects the most current and pertinent published information on interactions of MRE devices and associated equipment with the animals and habitats that make up the marine environment.

1.5 ANNEX IV 2016 STATE OF SCIENCE REPORT

The 2016 State of the Science report on environmental effects of MRE development begins with an overview of the state of knowledge for all of the plausible effects (**Chapter 2)** and provides an evaluation of the likely severity of those effects, as well as the probability of their occurrence. This assessment is very broad and

Table 1.1 Addressing risk to the marine environment in the 2016 State of the Science report.

Assessment of Likely Risk to the Marine Environment (consequence and probability)	**Action within the State of the Science Report**
Interaction appears to be a low risk for harm to the marine environment and is relatively well understood	No further consideration (for example, chemical releases)
Interaction probably offers a relatively low risk for harm, but requires more understanding	Chapter devoted to topic (for example, EMF)
Interaction is of higher priority for harm and requires more investigation	In addition to a focus in 2013 report, there is a major focus for chapters in this report (for example, collision of animals with turbines)

draws from a range of information from published sources, expert opinion, and other tools. In *Chapter 2*, each interaction is judged and further considered in Table 1.1.

Chapter 3 constitutes the greatest focus of the report. It provides details about the potential risk of marine animal collisions with tidal turbines, which represents the most active area of research in this field. This chapter builds on material presented in the previous Annex IV report published in 2013.

Chapter 4 focuses on the effects of underwater noise from tidal turbines and WECs on marine animals. This chapter builds on material presented in the 2013 Annex IV report.

Chapter 5 concerns changes in physical systems due to the generation of power from tidal and wave devices, based on changes in flow within natural waterbodies and the removal of energy from the system to be converted to electricity. This chapter builds on material presented in the 2013 Annex IV report.

Chapter 6 focuses on the effects of electromagnetic fields from power cables and moving or energized parts of tidal turbines and WECs. This chapter presents a compendium of information that has been collected over the past decade.

Chapter 7 looks at the potential effects on benthic habitats of the installation and operation of MRE devices, and also effects due to reefing of marine animals around devices.

Chapter 8 examines the role that marine spatial planning can play in siting and permitting marine energy, particularly in light of potential conflicts with fisheries and conservation activities. This chapter features input from most of the Annex IV participating nations.

Chapter 9 presents case studies of siting and permitting/consenting processes for MRE devices, and also features input from several of the Annex IV nations.

Chapter 10 summarizes the findings of the previous chapters and outlines a framework for monitoring around MRE devices to support development of the industry as well as critical research investments needed to retire certain risks or decrease the need for monitoring certain interactions. This may effectively streamline monitoring and mitigation over the life of marine energy projects.

1.5.1 SOURCES OF INFORMATION

Information used for the State of the Science report is publicly available, published work, derived either from peer-reviewed scientific literature or reports published by researchers, developers, and government agencies that represent the state of knowledge in the industry. Reports include monitoring and baseline assessment reports for specific projects, research studies that support specific MRE projects or address environmental interactions broadly, or guidance and assessments commissioned by governments to assist with the responsible development of the industry.

1.5.2
USES OF THE INFORMATION

The information gathered and analyzed for this report can help inform regulatory and research investigations of potential risks to marine animals and habitats from tidal and wave installations, and can assist MRE developers in developing engineering, siting, operational strategies, and monitoring options for projects that minimize encounters with marine animals and/or diminish the effects if such encounters occur. Used in conjunction with site-specific knowledge, the information from this report may simplify and shorten the time to permit (consent) deployment of single and multiple device arrays. The information brought together for analysis represents readily available, reliable information about environmental interactions with MRE devices; however, the analysis and conclusions drawn are not meant to take the place of site-specific analyses and studies, or to direct permitting (consenting) actions or siting considerations in specific location.

1.6
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2.0

Summary of Potential Environmental Interactions Associated with the Deployment of Marine Renewable Energy Devices

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As MRE technologies are installed, they will interact with and affect the surrounding marine environment in a variety of ways. Depending on the specific technology, certain stressors or components of each device may affect marine animals and habitats, also referred to as environmental receptors. Table 2.1 lists the key potential stressor-receptor interactions associated with MRE technologies (Boehlert and Gill 2010; Copping et al. 2013; Aquatera Limited 2012), and provides a brief description of each potential interaction.

This chapter provides a broad overview of the key stressor-receptor interactions associated with MRE technologies. The following chapters in this report will provide more information and details on many of these interactions, including extensive citations.

Section 2.2 describes each stressor (the rows listed in Table 2.1) in more detail, including the potential effects, focus of ongoing research, and our current understanding of the overall risk associated with each potential interaction. The remainder of this report will discuss those stressors identified with the greatest risk in more detail.

2.1 RISK

Risk can be defined as the likelihood of an adverse outcome from an action, and can be evaluated by the probability of the occurrence of an event, as well as its resulting consequence (Copping et al. 2015). Interactions with elevated risk are typically unlikely to occur but result in serious consequences, or occur regularly but more often than not result in non-significant consequences. In a new industry like MRE, there may be interactions between devices and marine animals or habitats that regulators or stakeholders perceive as risky. In many instances, this perception of risk is due to the high degree of uncertainty that results from a paucity of data collected in the ocean. However, the possibility of real risk to marine animals or habitats cannot be discounted; the lack of data continues to confound our ability to differentiate between real and perceived risks.

Examples of perceived risk driven by uncertainly of potential MRE effects include entrapment of a marine mammal among WEC or floating tidal mooring lines. The concern for the marine mammals arises from the uncertainty of how the animal might behave around the mooring lines, and whether the interaction might end in injury to the animal. Similarly, uncertainty continues to create a sense of risk for marine mammals, fish and seabirds around operating tidal turbines. While a collision with a turbine blade is an unlikely outcome for these animals, the potential consequences of a blade strike ensures that regulators and stakeholders will continue to be concerned. The real risk from these potential encounters of animals with parts of MRE devices could be better defined or removed (or retired) as serious threats with the collection of additional information from strategic research initiatives and monitoring around deployed devices. For further discussion of strategic research initiatives aimed at retiring risk and developing appropriate mitigation strategies, see Chapter 10.

Each stressor described in Sections 2.2 through 2.6 has been assigned a ranking of risk according to the potential risk it may pose to the marine environment:

LOW RISK **green**
MEDIUM RISK **yellow**
HIGH RISK **orange**

The risk score for each interaction is driven by both the uncertainty around the likelihood of and outcome of the specific interaction. For instance, a medium-risk interaction may not have a serious impact on the surrounding marine environment, but because it is constantly occurring the overall potential consequence is higher, which is reflected in the risk ranking. Conversely, a high-risk interaction may occur very infrequently but could result in a serious impact on marine animals. Because the overall risk associated with each stressor may change with the scale of a project, each stressor's risk assessment has been assigned for three project sizes: an individual MRE device; a small-scale project (~10 devices); and a large-scale commercial array (~100 devices) (see Tables 2.2 to 2.7 in ensuing sections). Though it is not common, some of the stressors discussed below pose different levels of risk to marine animals depending on whether the device generates energy from tides or waves. Because of this varying level of risk, the stressor risk tables may include an additional row to separate the risks for tidal and wave MRE devices. Each stressor risk table is shown at the beginning of the subsection; these tables are also combined and summarized in Table 2.8 (in Section 2.2.) to provide an overview of where the highest risks exist. It should be noted that while risk levels described in this chapter are representative of how most of the MRE community views these interactions, certain countries may have their own mechanisms for categorizing impacts as low, medium, or high risk. The following risk categories therefore may not correspond directly to a particular country's consenting regimes and processes.

Table 2.1. Key potential interactions between stressors associated with different MRE technology stressors and environmental receptors (Copping et al. 2013; Aquatera Limited 2012). Effects are described for single devices unless otherwise stated.

RECEPTOR	Static Device	Dynamic Device	Noise	Energy Removal	EMF	Chemicals
Marine Mammals	Changes in marine mammal/prey behavior; attraction or avoidance	Potential risk of collision with moving device; potential attraction or avoidance, change in behavior	Underwater noise from construction or operation may change animal behavior through attraction, avoidance, and disrupting animal communication and echolocation. Injury is possible for high source levels.	Effect not likely.	Effect not likely.	Effect not likely. Large releases of chemicals (such as oil) may affect resident marine mammals
Fish	Changes in fish behavior; may act as FADs or cause avoidance	Risk from moving device; collision	Significant source levels may cause injury in certain species. May alter behavior (attraction/avoidance)	Effect not likely. Larger projects may impact physical processes causing ecosystem cascade effect.	Potential effect on certain species' behavior (navigation, avoidance, attraction).	Chronic chemical leaching and large spills may affect resident fish species
Birds	If device has surface expression, birds may be attracted to the device or may avoid large numbers of devices; change behavior	Diving birds may be at risk from moving devices if they are within dive depth range.	Significantly loud devices with surface expression may affect bird behavior (avoidance).	Effect not likely. Large nearshore project could affect physical processes causing ecosystem cascade effect.	Effect not likely.	Effect not likely. Chronic leaching from large devices (predominantly nearshore) may affect resident seabirds.
Sea Turtles	Changes in turtle behavior; attraction or avoidance	Turtles may be at risk from moving devices; attraction or avoidance	Underwater noise may change turtle behavior; attraction or avoidance.	Effect not likely. Large nearshore project could affect physical processes and potential nesting habitat.	May affect turtle behavior; navigation, attraction, avoidance.	Effect not likely. Chronic leaching from large nearshore devices may affect nesting sea turtles.
Nearfield Habitat (benthic)	Devices may affect seabed and benthic communities in proximity to foundation	May affect benthic communities or nearfield physical processes such as scour	Effect not likely.	Effect not likely at single device. A large project may have effects on physical processes and benthic habitats.	May alter nearfield benthic communities; attraction or avoidance.	Effect not likely. Chronic leaching may affect nearfield environment and benthic habitat.
Farfield Habitat (benthic and pelagic)	Effect not likely	Effect not likely	Effect not likely.	Effect not likely at single device. A large project may have effects over larger distances on physical processes and benthic habitats.	Effect not likely.	Effect not likely.

2.2 POTENTIAL STRESSORS

This section elaborates on the interactions listed in Table 2.1 by describing the potential stressors listed in the table columns and the risks they may pose to the marine animals and environment (the receptors). Each section provides an overview of the stressor, the current understanding of how the stressor may affect each receptor, and how the interactions should be addressed moving forward. The following should be noted:

- This chapter broadly reviews each stressor-receptor interaction associated with MRE technologies. These interactions may vary depending on the type or species of animal; more detail about these interactions is provided in subsequent chapters.
- The benthic habitat and communities are categorized within both the nearfield and farfield habitat receptors in this chapter due to the potential effect MRE devices may have on them at different spatial scales; more biological detail is provided in Chapter 7.

Each stressor is scored low (green), medium (yellow), and high (orange) based on the potential risk associated with how they may affect marine animals and habitats for an individual device scale, for a small-scale commercial project, and for a large-scale commercial array. Different consenting regimes may have their own processes for undertaking these types of risk assessments; the risk levels documented here represent an overall consensus among the Annex IV nations.

2.2.1 STATIC DEVICES OR COMPONENTS

A static device refers to any component of a MRE technology that does not move, including the foundation of a device, mooring lines, power cables, anchors, and other components not in motion. Because of the wide array of different MRE technologies and the optimum location of each for extracting energy within the water column, static devices can be located on the seafloor, in the mid-water column, or at the sea surface. Marine animals interact with static devices by gathering near them (attraction), or avoiding them; there is no clear risk of animals colliding with static devices.

2.2.1.1 POTENTIAL EFFECTS OF STATIC DEVICES

One concern associated with the addition of MRE technologies and their static components into the marine environment is their ability to act as artificial reefs or fish aggregating devices (FADs), attracting certain marine animals such as fish, marine mammals, sea turtles, and birds (Kramer et al. 2015). Static devices, particularly those with large components attached to the seabed, may also potentially affect nearby rocky or soft-bottom benthic habitats and organisms. These changes induced by the installation of MRE devices may be beneficial for nearby habitats by acting as de facto marine reserves, providing refuge and increasing productivity, however not all research supports this concept (Inger et al. 2009; Wilhelmsson 2009). Conversely, MRE installations may alter the behavior of certain organisms by causing them to be attracted to or avoid the installed device, potentially increasing their risk of predation. This is likely to be of concern only if the population is already at risk from other factors such as overfishing and climate change. Large marine animals may also be at risk from colliding with or becoming entrapped in dense configurations of mooring lines (Benjamins et al. 2014), particularly in large-scale arrays. Entrapment can be defined as physically trapping a marine animal or causing confusion in or around a set of mooring lines, and is particularly a concern for MRE devices that are designed to be deployed with multiple mooring lines in close proximity to each other. If enough large static objects are placed in the marine environment, larger marine mammals may avoid the area altogether, keeping them from important feeding, mating, rearing, or resting habitats, or from vital movement and migratory corridors (Malcolm et al. 2010). Seafloor-based static components of MRE technologies may affect the nearfield benthic habit by attracting benthic organisms including potentially invasive species. Similarly, the presence of a static device on the seabed may cause scour in high-energy environments (Chen et al. 2013).

Table 2.2. Risk associated with static devices from MRE technologies (low risk [green], medium risk [yellow], high risk [orange]).

	Single Device Deployment	Small-Scale Project	Large-Scale Commercial Array
Static Device	low risk (green)	low risk (green)	medium risk (yellow)

2.2.1.2
PROGRESS TOWARD UNDERSTANDING

Data have been collected about fish and marine mammal behavior around structures in the ocean for many years prior to the development of the MRE industry. The concept of marine animals being attracted to structures such as static MRE devices in the marine environment is not new; studies of fish reefing around structures such as oil platforms, buoys, piers, and other foreign objects is well represented in the scientific literature. Studies have revealed which species and groups of fish are most likely to be attracted to or avoid static objects in the marine environment; however, there is still uncertainty around how these behaviors may affect or harm individuals or populations. There is no direct evidence that large marine mammals are at risk from colliding with or becoming entrapped in mooring lines or draped power cables associated with MRE devices. Similarly, there is no evidence that seabirds are likely to be unduly attracted to or harmed by association with static MRE devices.

2.2.1.3
INTERPRETATION OF THIS INTERACTION

While there is uncertainty about the degree to which marine animals will be attracted to or avoid static MRE devices, no data have been collected or extrapolated from surrogate industries that suggest these actions will result in significant adverse risk to individuals or populations. Due to the lack of data and information, further research and observations could help to dismiss (or retire) this risk. The potentially higher risk of dynamic devices (moving blades, etc.) to marine animals deserves greater attention (see Chapter 3 for more details). However, monitoring for animal interaction around moving devices (for example tidal turbines) would likely help determine the combined effects from the static presence and dynamic components of the devices. Modeling of large marine mammal interactions with mooring lines, coupled with field validation data, could help determine whether this interaction poses any real risk to populations.

Experience in field deployments to date indicates that interactions of marine animals with single static devices do not constitute a risk from foundations, anchors, mooring lines, etc. As more devices are placed in the ocean, uncertainty about the potential for mooring line entrapment may deserve more attention for large projects. Monitoring activities should evaluate animal behavior around MRE devices and their associated infrastructures to gain a better understanding of how these interactions may differ at larger-scale projects, particularly for large cetaceans. Until significant evidence is gathered to suggest these interactions could negatively affect marine animals, the potential interactions associated with static devices are considered to be of low priority that could be studied opportunistically as the industry progresses. However, the uncertainly around mooring line entrapment for large cetaceans with large commercial arrays raises the potential risk to a medium level concern.

2.2.2
DYNAMIC DEVICES

A dynamic device refers to any technology or component of a MRE technology that oscillates, rotates, or moves in a significant way. This includes, but is not limited to, rotating turbine blades and the various WEC designs that oscillate, attenuate, and move as waves pass. Because of the wide variety of MRE technologies, dynamic components of these technologies can be located above or below the sea surface; their potential environmental effects may vary due to their location in the water column and accessibility to certain marine animals. There may be concerns for marine animals colliding with moving parts of devices.

2.2.2.1
POTENTIAL EFFECTS OF DYNAMIC DEVICES

The possibility of marine animals colliding with dynamic components of MRE devices is the greatest challenge to siting and permitting. Because these devices rotate, oscillate, and move, it is possible that a marine animal in close proximity to a device could be

Table 2.3. Level of risk associated with dynamic devices from MRE technologies (wave and tidal MRE devices separated; (low risk [green], medium risk [tan], high risk [orange]).

	Single Device Deployment	Small-Scale Project	Large-Scale Commercial Array
Dynamic Device (Tidal)	medium risk	medium risk	high risk
Dynamic Device (Wave)	low risk	low risk	medium risk

at risk of colliding with, or failing to avoid, the moving components. Depending on the size of the technology or the speed at which it moves, these dynamic components may exert a great deal of force that may lead to serious injury or mortality. The greatest concerns are associated with marine mammal collisions with tidal turbine blades, particularly for those populations that are at risk from other factors, and for which the loss of a single individual could affect population stability (Carlson et al. 2013). Certain fish species may also be considered to be at risk from collision with tidal turbines based on their reefing habits and overall attraction to foreign objects in the marine environment (Hammar et al 2015; Amaral et al. 2015; Romero-Gomez and Richmond 2014), as well as diving birds from tidal blades located in shallow depths (~20 m or less) (Waggitt and Scott 2014; Grant et al. 2014).

Far less concern has been expressed about the potential risk to marine animals from moving parts of WECs (Furness et al. 2012). The dynamic nature of WECs such as point absorbers are generally thought not to pose a risk to marine animals; however, certain WEC technologies with a large surface expressions and moving parts, such as oscillating water column devices, may be of concern for seabirds and possibly sea turtles.

2.2.2.2
PROGRESS TOWARD UNDERSTANDING

A number of studies have been designed and implemented to evaluate the potential risk of marine mammals and fish colliding with wave and tidal technologies. Several of these studies have focused on monitoring animal behavior at planned wave and tidal energy sites to better understand how animals use these high-energy areas and how they might interact with MRE devices, once the devices are deployed. While these studies provide valuable baseline data and insight into how animals may use these high-energy areas, they do not address the uncertainty around marine animal behavior. Laboratory and semi-controlled field studies have also been conducted to examine fish behavior around turbines and to estimate potential survival rates after passing through turbine rotor-swept areas. The limited data collected from these studies suggest there is little reason to believe that fish will be at risk from colliding with tidal turbine blades. Although no large full-scale commercial arrays have been deployed anywhere in the world long enough to fully study their impacts, individual devices and small-scale projects have been installed. These projects have provided researchers with the opportunity to monitor animal behavior around MRE devices in the marine environment, and to begin to gauge the collision risk to marine animals. Other studies have included the use of numerical models to examine marine animal behavior to predict how animals may behave, react, and move around MRE devices in the environment. Modeling studies have also been developed to evaluate the biophysical properties of marine mammal skin and blubber and the potential forces exerted by tidal turbine blades to better understand the potential consequences of a collision. No data collected to date suggest a collision incident between a marine mammal and a tidal turbine will be fatal, or suggest that such an incident could be a common occurrence. Furthermore, there is still a great deal of uncertainty around how marine animals and fish will behave around dynamic MRE technologies.

2.2.2.3
INTERPRETATION OF THIS INTERACTION

Limited research activities have focused on better understanding marine animal behavior around MRE devices and the potential collision risk to animals. Some data have been collected that describe marine animal behavior around tidal devices and what the potential outcome of tidal turbine collision incidents may look like. There is still a great deal of uncertainty around the likelihood (or frequency) of these interactions occurring, as well as the severity of an incident (should it occur), and its effects on individual marine mammals, fish, seabirds, and their respective populations. Due to this high level of uncertainty, the interaction between marine animals and dynamic tidal energy devices and components is considered a higher priority perceived risk, especially as MRE installations increase in size. To add to the complexity of this issue, no collisions have ever been observed, likely confounded by the challenge of operating instruments continuously underwater in these high-energy environments. Therefore, these interactions should be considered as rare events that may not be observable if and when they occur.

Marine mammals are afforded a high degree of regulatory protection by most nations, a practice that drives research to focus on their potential collision with single MRE devices. However, there is little insight into how marine mammals (and other marine animals) will navigate multiple devices in an array. Because of this uncertainty, the level of risk associated with dynamic devices from large-scale MRE projects is higher than that of small-scale projects and single devices. Until researchers can better understand the potential severity and frequency of collision incidences, this potential interaction will continue to be of concern to regulators and stakeholders and will remain a priority research area.

2.2.3 NOISE

Noise can be generated by vessel traffic and in water construction, as well as by the installation, operation, and decommissioning activities required for MRE devices (Dubusschere et al. 2014). Besides operation, these activities tend to be of short duration. The loudest and most disruptive noise levels are associated with pile driving for installation of devices, although most MRE devices are likely to require small pilings or pin pilings only, installation of which generates much less noise than that required to install full sized pilings for offshore wind or other industrial activities in the ocean. Most MRE devices are anchored or placed on the seafloor, avoiding these construction activities. Vessel traffic associated with installation, maintenance, and decommissioning can also generate noise. Operational noise from MRE devices, though not continuous, is likely to last the life of the project and is of concern to a number of regulators and stakeholders.

2.2.3.1 POTENTIAL EFFECTS OF UNDERWATER ACOUSTICS

Sources of anthropogenic noise in the marine environment can be of concern to marine animals that use sound for communication, navigation, and hunting in the marine environment. The greatest concerns include the potential to mask echolocation sounds made by marine mammals for communication and navigation (Kastelein et al. 2013; Ellison et al. 2012). Risks may include changes in marine mammals' behavior for hunting, swimming, rearing, mating, resting, and avoiding underwater threats, as well as changes in migratory patterns if sufficient noise were generated. Fish may also be at risk if they are attracted to a device by its physical presence or the sound emanating from it. In addition to the underwater sound generated that may mask fish hearing, experimental data exposing fish to turbine sounds over long periods of time resulted in tissue damage (Halvorsen et al. 2012). As the scale of projects increases, the cumulative impacts of underwater sound may increase and cause additional masking or other effects at greater distances from the source. Construction and decommissioning activities such as pile driving and increased vessel traffic are also of concern due to the potential for generating high-intensity sound and sound pressure levels which may permanently affect an animal's hearing, damage sensitive tissue, or further affect its behavior (Finneran 2015). The application of acoustic deterrent devices has also been explored for construction activities and the operation of MRE projects in certain regions and countries, which may introduce more anthropogenic noise into the marine environment (Carter and Wilson 2013).

2.2.3.2 PROGRESS TOWARD UNDERSTANDING

A majority of the acoustic research to date has focused on accurately measuring the sound output from MRE devices, and little is known about how the acoustic output of these devices will affect marine animals. Studies have examined how mechanical sound generated by MRE devices can alter marine mammal behavior and affect fish and seabirds (above water); such examinations includes determining sound thresholds and frequencies for altering marine animal behavior and/or causing tissue damage. A small number of baseline studies have recorded ambient underwater acoustic data in high-energy environments pre- and post-installation for comparison post-installation. Some data suggest the acoustic output of MRE technologies may influence marine animal behavior such as attracting animals or causing them to avoid the area; however, no data collected to date have suggested that the operation of MRE technologies will surpass the sound thresholds to cause injury or cause tissue damage in marine animals. Acoustic data have also been collected for installation and decommissioning activities from analogous industries as well as MRE devices to gauge

Table 2.4. Level of risk associated with acoustic output from MRE technologies (low risk [green], medium risk [amber], high risk [red]).

	Single Device Deployment	Small-Scale Commercial	Large-Scale Commercial
Acoustic	low risk (green)	medium risk (amber)	medium risk (amber)

how loud certain activities may be. While these studies have been technology- and site-specific studies, they have provided a baseline understanding of how loud these devices and activities might be, and how they may affect marine animals.

2.2.3.3
INTERPRETATION OF THIS INTERACTION

Underwater acoustic data collected for different designs of MRE devices help inform the industry about the levels of additional sound that may be introduced into the marine environment. Existing measurements of operational noise levels from wave and tidal devices suggest that noise is not likely to be at levels to cause injury or significant behavioral effects. Almost all data collection has occurred around single devices; although we can bound the likely acoustic outputs from the cumulative impacts of arrays, few field measurements have been made to date. There is even more uncertainty around whether these levels will affect marine animals. Noise levels associated with pile driving and other installation and construction activities are more likely to affect marine animals for short durations in the vicinity of the project, depending on the particular animal species, distance from the installation, and oceanographic conditions.

To date, there is little evidence that the operation of MRE devices will significantly affect marine animal behavior, but pre- and post-construction ambient acoustic data collection may be required for many projects until a better understanding is reached. There is still a great deal of uncertainty around how the acoustic output of long-term deployments and large-scale projects may affect marine animals; research is still needed to fully understand this interaction. Acoustic data for MRE construction, maintenance, and decommissioning activities are likely to be required to understand these effects. Because of the high level of uncertainty associated with understanding how the acoustic outputs from MRE technologies will affect marine animals and whether these effects will compound as deployments increase in size, this interaction is considered a medium-priority perceived risk, particularly with larger-scale projects.

2.2.4
ENERGY REMOVAL AND CHANGES IN FLOW

The placement of tidal or wave devices in the marine environment will inevitably change the circulation of the water (tidal) and/or change the incident wave heights (wave). In addition, by removing kinetic energy to generate electricity, system processes such as circulation, sediment transport, and mixing will be altered. Depending on the specific location and the amount of energy removed, these changes can affect the marine environment.

2.2.4.1
POTENTIAL EFFECTS OF ENERGY REMOVAL

If large amounts of kinetic energy are extracted from the marine environment, the natural movement of water will be altered, thereby changing flows throughout the water column and affecting many processes, including mixing, flushing, and sediment transport. These changes in flow can result in scour around foundations and anchors, and could have profound biological ramifications such as causing changes in benthic habitats and sediment deposition; alterations in flushing rates for oxygenated water in enclosed waterbodies that can affect water quality; changes in the mixing and water column stratification that could affect primary production and marine food chains; and changes in water movement responsible for the distribution of planktonic larvae of animals and/or seeds and propagules of marine plants (Copping et al. 2013).

2.2.4.2
PROGRESS TOWARD UNDERSTANDING

Parameters that determine water circulation are commonly measured in marine waters, but less is known about high-energy sites that have potential for wave and tidal power development (Shields et al. 2011). Similar data have been collected at selected marine energy development sites prior to development, along with detailed inflow and turbulence data to support the engineering of devices. However, very few data have been collected, at only a handful of tidal marine energy development sites, after devices have been deployed, and even fewer at wave energy sites. Researchers

Table 2.5. Level of risk associated with energy removal from MRE technologies (low risk [green], medium risk [tan], high risk [orange]).

	Single Device Deployment	Small-Scale Commercial	Large-Scale Commercial
Energy Removal	[low risk]	[low risk]	[medium risk]

depend largely on the use of hydrodynamic models to simulate physical processes and their interactions with MRE devices. These models vary in accuracy and complexity, and primarily focus on analyzing changes in water flow and other dependent processes such as transportation of sediment, changes in water quality, and the growth of marine organisms (Kadiri et al. 2012). Several hydrodynamic models have been used to examine effects of single devices or arrays on the physical environment and biological features. The models all indicate that the installation of small numbers of devices is unlikely to have an effect on waterbodies. The models also indicate that very large numbers of turbines or WECs (>100) will be needed to measure changes in circulation that may have biological or ecosystem-wide consequences (Yang et al. 2014). Recent modeling efforts have also focused on identifying the tipping point of specific basins. The tipping point can be considered as the amount of extracted energy that will cause a detectable change in the basin's physical processes that may lead to a breakdown of ecosystem processes. Better understanding of these thresholds enables researchers to estimate the number of installed MRE devices needed to cause significant effects on physical processes.

2.2.4.3 INTERPRETATION OF THIS INTERACTION

Hydrodynamic models provide valuable information about and insight into how the installation of MRE devices may affect physical processes; however, data are needed to validate these models and strengthen their results. As more types of devices are installed, it will be important to collect hydrodynamic data pre- and post-installation to gain a better understanding about how operating devices may affect physical processes. The modeling exercises targeting a waterbody's tipping point are fairly theoretical, but they provide researchers, developers, and regulators with a better sense of how much energy could be removed from a physical system before detrimental effects may occur. There is still a considerable amount of uncertainty around how small- and especially large- scale commercial projects may affect physical systems. Because of this uncertainty, this interaction remains to be a perceived risk for the marine environment at larger scales. All the modeling studies, and the limited data collected so far, suggest that small MRE projects will not have adverse risks on the marine environment, so the risk associated with the interactions from these small projects should be considered low. Additional hydrodynamic data derived from multiple device deployments and more powerful models are crucial for better understanding interactions at larger-scale MRE farms.

It is clear from recent hydrodynamic data collection efforts and models that small-scale projects or individual devices will not have a noticeable effect on the physical systems or biological processes. Modeling studies focused on identifying a tipping point within specific physical systems have found that a very large number of MRE devices could be operated before a noticeable effect on a physical system would occur. In most cases, the number of devices would be in the thousands—an unlikely number to be considered for a range of reasons, including navigational risk, blockage of a passage, and unacceptable risks to other human uses of waterways. However, the overall question of how certain MRE projects may affect physical systems is of importance to many regulators because of the strong connection between and dependence of water quality and key biological processes on the physical movement of water within a system. Hydrodynamic models should continue to evaluate the potential effects large MRE developments may have on physical systems to reduce uncertainty, and data should be collected around existing devices and projects to validate these models and provide a better understanding of this interaction and where a specific system's tipping point may exist.

2.2.5 ELECTROMAGNETIC FIELDS

Electromagnetic fields (EMFs) are generated as electricity is transmitted through cables or from moving parts of machines. The electrical field can be contained by a grounded metallic sheath and rapidly diminishes in the marine environment; however, the magnetic field can persist for longer distances and induces a secondary electrical field. Although the Earth has a naturally occurring static geomagnetic field generated by Earth and tidal motions, additional EMF signatures in the marine environment may affect certain organisms. Anthropogenic EMF signatures are not new to the marine environment because many subsea cables, bridges, and tunnels have been deployed and currently provide measurable electromagnetic signatures in the ocean.

2.2.5.1
POTENTIAL EFFECTS OF EMFS

As more power cables are installed and MRE devices are deployed in the marine environment, there is concern that the EMF signatures emitted from the power cables, moving parts of devices, and underwater substations or transformers may affect marine organisms that use the Earth's natural magnetic field for orientation, navigation, and hunting. Marine organisms such as certain species of elasmobranchs (cartilaginous fish), marine mammals, crustaceans, sea turtles, and other fish species have electro- or magneto-receptors that allow them to detect electrical or magnetic fields (Bedore and Kaijura 2013; Putman et al. 2014). The introduction of additional EMF into the marine environment can potentially disrupt or alter these animals' ability to detect or respond to natural magnetic signatures, potentially altering their survival, reproductive success, or migratory patterns (EPRI 2013).

2.2.5.2
PROGRESS TOWARD UNDERSTANDING

To better understand how EMFs may affect marine animals, scientists have identified marine organisms that are known to be sensitive to magnetic and electrical signatures to better understand the mechanisms by which these animals detect EMFs and how they behave around specific levels of EMFs. Scientists have also modeled potential EMF signatures for power cables and MRE devices, providing an estimate of how far electrical and magnetic signatures may persist from a given cable. To understand how certain animals may be affected by EMFs, laboratory studies have been designed to determine whether EMFs may affect certain species of interest, and if so, to understand the specific mechanism of potential harm. Mesocosm and field studies have been used to better understand how EMFs may affect animals in the marine environment, and whether the introduction of additional EMFs may affect their movement patterns and migrations. The potential effects of EMFs are not unique to the MRE industry; other analogous industries such offshore wind and telecommunications use multiple cables and technologies to transmit electricity and data back to shore.

2.2.5.3
INTERPRETATION OF THIS INTERACTION

Laboratory and field studies have suggested changes in certain animal behaviors due to exposure to EMF signatures; however, no data have been collected that suggest that additional EMFs in the marine environment will have significant effects on marine animals. It is unclear what level of effect of EMF signatures might be expected, as indicated by laboratory and field studies. Because of the lack of data and high uncertainty associated with the potential effect, the interaction between EMFs emitted by the MRE device and cables and marine animals is a low risk for small MRE farms. The level of risk may rise as the industry develops larger, longer-term projects, increasing and prolonging the potential EMF exposure to marine animals.

Because of the status and regulatory protection of several marine animals known to be sensitive to EMFs, the potential EMF effect from certain MRE projects is still under scrutiny. To address the remaining uncertainty of this interaction, carefully designed laboratory and field studies will be needed to understand how EMFs may affect certain animals, particularly for larger-scale projects. Information from analogous industries such as offshore wind can inform researchers, regulators, and developers about the current state of the knowledge of EMF effects, and help plan future laboratory and field studies.

2.2.6
CHEMICALS

Chemicals may leach into the marine environment from coatings or paint on exterior surfaces used to prevent biofouling and/or corrosion, or chemicals spilled into the surrounding area from vessels or malfunctioning MRE devices. These sources typically allow very small rates of chemical input on an ongoing basis and are well understood because they resemble inputs from boat bottoms and other marine industries. Chemicals such as petroleum or hydraulic fluids may also be spilled into the marine environment from vessels or malfunctioning MRE devices. Spill events typically

Table 2.6. Level of risk associated with EFM from MRE technologies (low risk [green], medium risk [tan], high risk [orange]).

	Single Device Deployment	Small-Scale Commercial	Large-Scale Commercial
EMF	low risk	low risk	medium risk

result in larger quantities of chemicals being released into the marine environment, but occur over a shorter period of time. The overall likelihood and therefore risk from spills into the marine environment is very small.

2.2.6.1
POTENTIAL EFFECTS OF CHEMICAL LEACHING

The leaching of chemicals into the marine environment can have a wide range of potential effects on the marine animals and habitats, depending on the toxicity and quantity of the material. Different technologies such as shallow tidal devices may also use stronger antifouling paints or biocides than typical wave or deeper tidal devices to better control or eliminate biofouling. A slow chronic release of biocides or antifouling paint can potentially affect water and sediment quality, and if the source is large enough and the leaching event occurs for long enough it may result in bioaccumulation of chemicals in primary producers and consumers, thus potentially affecting the entire food chain (Votier et al. 2005). Spills or acute releases of chemicals from lubricants, hydraulic fluids, vessel fuel, or other petroleum-based products may have a more significant impact on the local marine animals and habitats if the spill is large and covers a wide area (Massey 2007).

2.2.6.2
PROGRESS TOWARD UNDERSTANDING

The potential environmental effects of both chronic leaching of chemicals from biocides and antifouling coatings and accidental spills of oil, fuel, and other chemicals have been studied for other industries such as offshore wind energy, oil and gas, shipping, and other harbor- and port-related activities. Research on historical incidences of large chemical and oil spills has also provided researchers with a good understanding of how certain levels of different chemicals may affect marine animals and habitat, and regulations are in place in developed nations to manage and limit damage from spills.

2.2.6.3
INTERPRETATION OF THIS INTERACTION

Of all the potential stressor-receptor interactions associated with MRE technologies, the effect of chemicals on the surrounding environment is best known. There is a good understanding of the potential effects certain chemicals may have if leached into the marine environment because each commercially available paint and coating has undergone rigorous approval testing and processes. For this reason, the interaction between chemicals associated with MRE developments and the marine environment is not driven by uncertainty, and can be considered a low priority risk. It should be noted that new biocides and anti-corrosion materials may be developed for MRE devices; if new materials are developed, they will also require testing and approval before use. The greatest potential risk from chemicals associated with marine energy development will be from installation, maintenance, and decommissioning vessels that carry fuel oil and other forms of hazardous substances. These risks are well documented and understood for other sectors.

The similarities to paints and coatings used by other marine industries, and the use of standard or purpose-built work vessels for work at sea, ensures the risk from chemicals in the marine environment will be mitigated by standard marine practices.

2.3
UNDERSTANDING RISK

As the MRE industry develops, it is important to acknowledge all of the potential mechanisms of harm these technologies may pose to the marine environment, although many of the perceived risks are likely to be small and easily avoided or mitigated. All of the pertinent risks to the marine environment from tidal and wave energy development are collated (in Table 2.8) and assigned a level of risk. As mentioned earlier, most of these risks are driven by uncertainty and most of them can probably be better understood and perhaps

Table 2.7. Level of risk associated with chemical leaching from MRE technologies (low risk [green], medium risk [tan], high risk [orange]).

	Single Device Deployment	Small-Scale Commercial	Large-Scale Commercial
Chemical Leaching	low risk (green)	low risk (green)	low risk (green)

retired, with additional strategic research investments. In each case, the assignment of a medium or high risk (yellow or orange) is most likely due to uncertainty about the mechanisms of risk, the likelihood of the occurrence, and the potential consequences to the marine receptors.

The remainder of this report focuses largely on the state of the science for high- and medium-risk interactions (yellow or orange in Table 2.8) and includes information about current research efforts and progress toward understanding most interactions and reducing the uncertainty associated with them. Chapter 10 of this report will coalesce the information and provide a look at methodologies and approaches for monitoring these interactions and addressing some of these higher priority perceived risks through strategic research, propose mitigation for remaining risks, and estimate the approximate scale of costs for monitoring and strategic research investments to effectively protect the marine environment while enabling the marine energy industry.

To effectively advance the industry, researchers must begin to alleviate concerns raised by regulators and assist the industry in navigating siting and environmental permitting/consenting processes. Research efforts are needed that focus on addressing the highest risk potential interactions in order to reduce the uncertainty that is driving so many of these risks. The highest risk (orange) is still the interaction of marine animals with large numbers of dynamic devices, most specifically, rotating tidal turbine blades. This risk is explored in Chapter 3, Collision Risk for Marine Animals around Tidal Turbines. The risk from underwater noise generated by turbines and WECs is one of the interactions of medium concern, and is explored further in Chapter 4 (updated since the 2013 Annex IV report).

Most interactions and associated risks from single devices are unlikely to harm the marine environment until larger arrays are deployed; such arrays may require monitoring and strategic research to prepare for the commercial development of the industry. Each of these interactions is discussed in more detail in subsequent chapters of this report: the presence of dynamic devices in the marine environment (Chapter 3); EMF outputs from cables and devices (Chapter 6); the removal of energy and changes in flow in waterbodies (Chapter 5 –updated since the 2013 Annex IV report); and effects on benthic environments and from fish attraction (or reefing; Chapter 7). Chemicals are not further addressed in this report as this interaction is very well understood from other industries.

While the high-priority interactions that have the most uncertainty and perceived risks may require pre- and post-installation monitoring and possibly mitigation, the medium-priority interactions or those risks that fall in the middle of the risk spectrum, (which includes many interactions listed in Table 2.8) exhibit significant information and data gaps. Due to this uncertainty, regulators may still require project developers to monitor for these interactions pre- and post-installation. If some of the uncertainties associated with these medium-priority perceived risks can be reduced through strategic research efforts, or potentially retired altogether, a lower intensity of monitoring may be required, thus simplifying the overall siting and permitting/consenting process.

Table 2.8. Summary of MRE device stressors and the potential risk they pose to the marine environment (low risk ■, medium risk ■, high risk ■).

Stressor	Single Device Deployment	Small-Scale Commercial	Large-Scale Commercial
Static Device	Low	Low	Medium
Dynamic Device (Tidal)	Medium	Medium	High
Dynamic Device (Wave)	Low	Low	Medium
Acoustic	Low	Medium	Medium
Energy Removal	Low	Low	Medium
EMF	Low	Low	Medium
Chemical Leaching	Low	Low	Low

2.4
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3.0 Collision Risk for Animals around Tidal Turbines

The potential for marine animals to collide with the moving parts of tidal devices, particularly the rotors of horizontal-axis tidal-stream turbines, is a primary concern for consenting/permitting and licensing of tidal developments. The importance of this issue, associated definitions, and the need to understand collision risk in general, and for mammals, fish, and seabirds, in particular, are discussed in the following sections.

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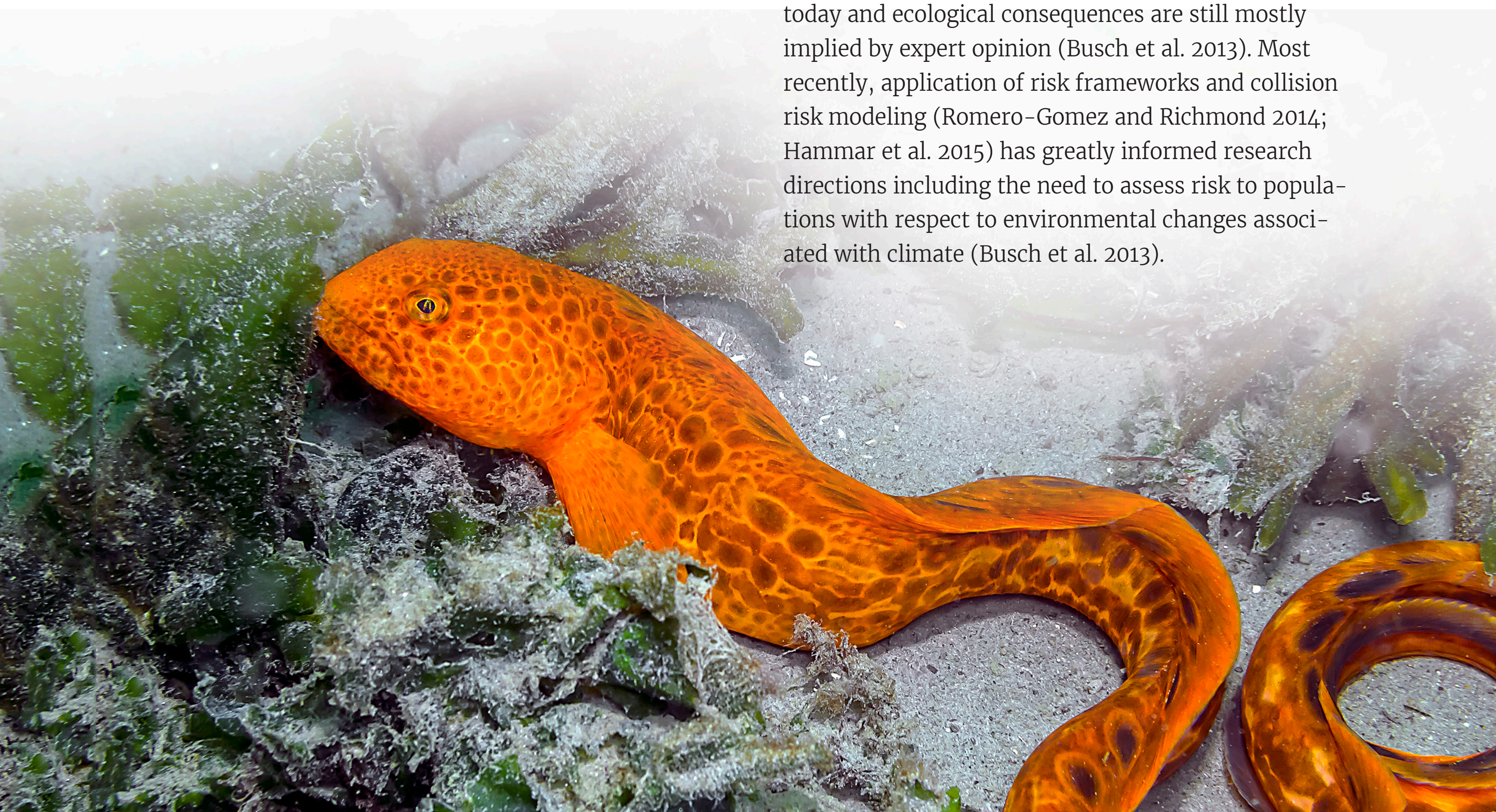
3.1 IMPORTANCE OF THE ISSUE

Animal interactions with tidal turbines is an active area of research because many questions remain today and ecological consequences are still mostly implied by expert opinion (Busch et al. 2013). Most recently, application of risk frameworks and collision risk modeling (Romero-Gomez and Richmond 2014; Hammar et al. 2015) has greatly informed research directions including the need to assess risk to populations with respect to environmental changes associated with climate (Busch et al. 2013).



Where proposed tidal energy projects overlap with the habitat of protected species there are concerns that collisions could lead to injury and mortality of individuals, and in some cases affect the long-term status of the population concerned. Of particular concern are populations that are protected because of their increased vulnerability to external factors that threaten their viability. Examples of this special protection include the species listed in the Endangered Species Act of 1973 and Marine Mammal Protection Act of 1972 in the United States, the Species at Risk Act in Canada, or the Council Directive 92/43/EEC, as amended, on the conservation of natural habitats and of wild fauna and flora (Habitats Directive) in Europe. The area most studied for MRE development—northern Scotland—has provided no indication that the harbor seal population has declined as a result of MRE development; however, the industry is subject to intense scrutiny because of the fragile status of this population, even if MRE-related risks might turn out to be very limited.

As noted in Chapter 2, risk to an animal in the vicinity of an MRE device is defined as the likelihood of an adverse outcome from an action, and can be evaluated by the probability of the occurrence of an event as well as its resulting consequence.

Few studies of the consequence of an animal colliding with an MRE device have been completed, although concerns about potential blade strike on the highly endangered Southern Resident killer whales prompted a study to define the likely risk to these killer whales, and the project was able to proceed to licensing (Carlson et al. 2013). This concern threatened to stall permitting of two OpenHydro tidal turbines in Admiralty Inlet, Puget Sound, by Snohomish County Public Utility District No. 1; the project has since been put on hold due to funding issues.

Before modern tidal devices were installed, lists of potential stressors (physical features of the device) on the natural environment were produced (Gill 2005; Čada et al. 2007; Boehlert and Gill 2010; Polagye et al. 2011). The hypothetical effects and impacts, particularly the severity of collision, were primarily based on past knowledge of fish collisions with conventional hydropower turbines (Čada et al. 2007) and barrage-based tidal power developments (Retiere 1994; Gordon 1994). Generally, impacts of tidal turbines on marine life are projected to be less than those of conventional hydropower turbines (Romero-Gomez and Richmond 2014; EPRI 2011) because of the open design of the tidal turbines and slower rotational speeds. Despite this, collision risk remains the most cited concern from the general public and remains one of the most elusive effects to observe. Direct observation of animal movements and behavior in the vicinity of devices is considered the best input to evaluations of risk and impacts (ABPmer 2010) and to answer stakeholder and regulator questions about the risk of animals encountering turbine blades (Copping et al. 2013; Johnson et al. 2015; Jansujwicz and Johnson 2015b). Concern about collision risk continues to be at the center of research for MRE development.

Current uncertainty about the nature and magnitude of collision risk is curtailing the rate of the development of the tidal energy industry in some parts of the world; for example, in Orkney in northern Scotland, where the harbor seal population has declined by 78% between 2000 and 2013 (SCOS 2012), constraints have been placed on tidal developments until more information is available about the risks tidal turbines represent to this species. This is particularly important because Orkney has long been promoted as a site with some of the world's best tidal resources; the majority of projects announced in the world's first leasing round for commercial marine energy generation are located in Orkney waters and around the northern coast of Scotland. In the USA, the Marine Mammal Protection Act raises protection of all marine mammals to a very high level; those populations, like the Southern Resident killer whale that are endangered, are afforded the highest protection against injury or death of a single individual. Similarly, concerns have been raised about the potential to injure or kill fish passing through tidal turbines, and in the UK and other parts of Europe, concerns about risks to diving birds from turbine blade strike have also been raised.

Incremental steps have been taken to generate relevant data about MRE tidal power devices and their associated environments to inform the estimation of collision risk. Population data for tidal-stream environments are generally poorly documented due to the difficulties of conducting quantitative sampling in such areas. However, several areas have now been characterized (Broadhurst et al. 2014; Vieser 2014) and techniques for doing so are evolving. Equipment and novel methods have been tested in laboratory and field studies to observe fish around MRE turbines, and quantitative models and risk assessments are being used to better inform decision-making for marine mammals, seabirds, and fish. There is a need to integrate research to effectively coordinate efforts to best inform MRE collision research. A first step in doing so is to use common language and definitions.

3.2 DEFINITIONS

This section compiles recent research progress and language used to date, with some suggestions for a cohesive path forward to better inform MRE collision risk. Table 3.1 (at the end of the section) summarizes definitions that are useful for understanding interactions with MRE devices.

3.2.1 COLLISION

Collision is defined as the physical contact of one object with another, usually with some inference of a negative result. The objects of concern are MRE device components (stressors): non-moving (static) and moving (dynamic) and natural objects (receptors; in this case marine animals) in the vicinity of the device. Collision can be considered from two perspectives, the stressor contacting the receptor, or vice versa. One perspective implies harm to the receptor (object in the environment) and the other the stressor (the device). General consideration to date has been from the perspective of damage to the receptor (Wilson et al. 2007; Schweizer et al. 2011; Amaral et al. 2014, 2015; Castro-Santos et al. 2015). It should be noted that studies have also focused on the potential damage to a turbine that might occur from a collision with a whale or a large man-made object (Longshaw et al. 2014); however, the focus of this report is on potential harm to the marine animal rather than the turbine.

A collision of an MRE device part with a marine animal has been considered an interaction that results in physical injury (even slight) to the animal (as in Wilson et al. 2007) that can involve parts other than just a turbine blade (in the case of a tidal turbine). Other MRE device parts include fixed submerged structures, mooring equipment, turbine rotors, and, depending on device design, structures that may form traps. In addition, an animal could interact with the pressure field around a blade. Therefore, an extension of the collision definition has included the pressure field coming in contact with an organism and resulting in injury (Wilson et al. 2007). This definition of collision implies physical contact or an interaction with the immediate pressure field around a turning part of the device.

Collision has also been defined without implying interaction with pressure fields around devices. For example, Romero-Gomez and Richmond (2014) define interactions with the rotating/dynamic parts of a tidal power device, not implying any interaction with the pressure field around the device, and they imply that a collision is only detrimental if it results in injury or mortality. Pressure fields around turbines have the potential to affect interactions with small fish that cannot actively evade the flow, while larger fish, marine mammals, and seabirds are unlikely to be affected.

Nuances in this definition may be related to determining the actual interactions between the animal and the device, which have yet to be well characterized or observed (Amaral et al. 2015; Hammar et al. 2013). The definition of "collision"—specifically, whether it should include the pressure field around the turbine blades themselves—needs to be clarified. The importance of the pressure field is associated with the preconceived notion of similarity between conventional hydropower turbines and MRE turbines. However, MRE tidal turbines are generally larger than conventional hydropower turbines (1 - 16 m vs 1.5 – 9 m, respectively), have slower rotational speeds (5 – 70 rpm vs 50 – 100 rpm) and blade tip velocities (18 – 32 m/s vs several hundred m/s) (ABPmer 2010). These differences result in tidal turbines producing smaller changes in shear stress, turbulence, and water pressure, which could result in less damaging collisions and potentially better survival rates (EPRI 2011). This is supported by a computational model to show that there was a maximum pressure drop across a simulated rotating tidal turbine blade of approximately 2,000 Pa, which is low relative to harmful pressure changes of 340,000 Pa (Becker et al. 2003) around conventional hydropower turbines (from ABPmer 2010). As such, inclusion of the pressure field around an MRE tidal device as part of collision risk is questionable. We suggest, for tidal turbines, that the pressure field not be included in the definition of collision until these pressure fields are more precisely defined to have negative consequences for individuals.

3.2.2
RELATED INTERACTIONS

Contact with a rotating part requires the following conditions, which introduce additional behaviors that can be categorized as interactions: 1) inability to avoid/evade; 2) crossing the rotor-swept area; and 3) collision (Romero-Gomez and Richmond 2014). With respect to consequences for the animal, to be killed it must 1) inhabit or pass through the waterbody of an MRE device; 2) become unavoidably entrained in the water in front of a turbine and/or choose to remain in the flow; 3) be struck by a rotor; and 4) receive lethal injuries (Amaral et al. 2015). While collisions with moving objects do not always result in injury and mortality there is much uncertainty about mortality rates for MRE turbines since tidal turbine tip velocities, while still lower than those of conventional hydropower turbines, can be greater than 8 m/s (Fraenkel 2006), similar to tail slap velocities used by killer whales (up to 8 m/s) to kill fish (Domenici et al. 2000) or the velocities at which ship strikes can cause mortality (14 knots or faster, equivalent of approximately 7 m/s) (Laist et al. 2001). Injury that may be caused by collision between a marine animal and a moving object is also a function of the mass of the two objects.

3.2.3
EVASION AND AVOIDANCE

Evasion and avoidance have been used to describe behavior prior to contacting a device, and are critical for assessing collision risk. These behaviors can be defined relative to the animal's distance from the object or in relation to the sensory and behavioral modality of the response. Avoidance has been associated with a change in behavior that occurs at a long range from an object (i.e., avoiding the area within the region of a device), related to receiving some sensory stimulus from the MRE device, and can be split into macro avoidance and meso avoidance. Macro avoidance includes all behavioral responses, including attraction, displacement, and barrier effects, to the presence of a device occurring beyond its perimeter. The distance at which birds fly around wind turbines exhibits this behavior and has been estimated to be greater than 500 m from the base of the outermost device. It is not clear that a distance will hold great meaning to animals approaching tidal turbines; most likely the response distance will be related to the sensory capabilities of the animal. Meso avoidance includes all behavioral responses, including in-flight deflection, and functional habitat loss, to the presence of a device occurring outside the immediate footprint of the device (perhaps on the order of 10 m from the device) and within the perimeter of the array area (perhaps 500 m from the base of the outermost devices). Evasion is a close-range behavior (i.e., one that occurs during a close encounter with a turbine blade) (ABPmer 2010).

The "long-range" distance at which macro or meso avoidance may take place has been defined as a distance farther away than a visual response can be undertaken by the animal. Responses at the maximum extent of this range are dictated by sensing noise or vibrational cues, or in the case of pinnipeds, mechanosensory systems such as their whiskers. At "close range," evasions by fish are likely dictated by visual clues (ABPmer 2010), but could also be informed by changes in hydrodynamics near the device. Marine mammals are particularly reliant on sound, while birds are likely to rely on vision as a primary sense. Others have defined these distances based on the physical size of the device, where evasion is defined as within one to two diameters of the device and avoidance is defined as a response at greater than two diameters from the device (Copping et al. 2013).

To avoid a collision several levels of successful behavior must occur: 1) object detection; 2) threat assessment; 3) evasion initiation; 4) successful evasion. Predator-prey encounter rate models have been applied to encounters between marine animals and MRE devices to understand avoidance and evasion (Wilson et al. 2007). Avoidance is defined as "maneuvering for position by prey, before the predator starts a chase," while "evasion" is an escape response to an attack, with optimal evasion involving "…escape at a small angle (up to 20°) from the heading directly away from the predator" (Weihs and Webb 1984). In the context of collision with MRE turbines this could be restated as evasion involving a "last-minute" escape response, in the absence of which, the animal would be struck by the device. To apply a predator-prey encounter model the following are needed: 1) the density of the animals in the locale of the turbine, 2) the velocities of both the animal and turbine blades, and 3) the encounter radii of the animals and the turbine blade (Wilson et al. 2007).

3.2.4 ATTRACTION

Because the effects of MRE devices on animals are dependent on their presence in the region of the device (Wilson et al. 2007; ABPmer 2010; Romero-Gomez and Richmond 2014; Amaral et al. 2015), it is worth considering the added risk associated with animal presence because it might be related to attraction to a new structure in the animals' environment. The influence of small pelagic fish gathering in an area could influence the presence of larger, predatory animals. The attraction of animals to man-made structures is regularly used to man's advantage; e.g., use of FADs to enhance fishery opportunities (e.g., Brock 1985). For more information on FADs and fish reefing, see Chapter 7. However, in areas with high flow rates such as tidal rapids, fish may be unlikely to aggregate for long periods (ABPmer 2010). This should be considered when assessing collision risk because even areas of lower turbulence around devices might appear to provide shelter, but they are not likely to be extensive enough for flow refuge.

3.3 UNDERSTANDING COLLISION RISK

A general conceptual framework has been developed for understanding the risk of marine animals colliding with MRE devices (Figure 3.1). The framework is intended as a frame of reference for assessing the current status of the science surrounding this issue.

The key to estimating the risk from MRE devices is recognizing that impacts on populations of marine mammals, fish, and seabirds are of concern for maintaining a thriving marine environment; however, collision risk is estimated as it affects the individual. This conceptual framework begins with the potential effects on individual animals from MRE devices and works toward effects on populations.

A number of key factors contribute to collision risk. It may be helpful to think of the process of predicting the magnitude and significance of collision risk for a particular project as a combination of the predicted encounter rate (or

Table 3.1. Summary of definitions useful for understanding interactions with MRE devices.

Term	Definition	Comments
Encounter	To be in the presence of an MRE device	May lead to a collision if the animal in question does not take appropriate avoidance or evasive action (Wilson et al. 2007); however, animals may pass through a turbine blade without injury, depending on the speed of the blade, speed, and size of the animal.
Collision	Physical contact of one object with another; any part of an MRE device (not just a blade), usually with some inference of a negative outcome	Includes the pressure field around the blade (Wilson et al 2007). Conventional hydropower turbines are generally smaller (1.5 – 9 m diameter) with higher rotational speeds (50 – 100 rpm) and blade tip velocities (18 – 32 m/s) therefore may not need to include the pressure field (ABPmer 2010) in the definition of collision with an MRE turbine. Does not always imply injury (Amaral et al 2015).
Evasion	To change behavior in close proximity to an object to avoid an impact (ABPmer 2010)	Informed by predator-prey behavior (Wilson et al 2007).
Macro Avoidance	Behavioral responses occurring beyond the perimeter of a tidal device array at a distance from the base of the outermost device (distance estimated to be greater than 500 m for birds and wind turbines; yet to be defined for tidal devices)	Informed by predator-prey behavior (Wilson et al 2007): maneuvering for position by prey, before the predator starts a chase.
Meso Avoidance	Behavioral responses to the presence of a turbine occurring outside the footprint of the tidal device and within the perimeter of the tidal array	
Avoidance	To change behavior at some distance away from an object (ABPmer 2010)	

transit rate) with the predicted collision probability, leading to a prediction of the number of individual collisions between the MRE devices and marine animals. The most important predictors of potential animal encounter at an MRE device are animal density and behavior at the depth of the device. Avoidance responses will reduce the density of animals around devices, reducing the risk of collision. The most important factors in determining the probability of a blade strike are the physical characteristics of the device (blade shape, size, and rotational speed), the characteristics of the animal (swimming behavior, body size, and approach angle), and the ability of the animal to take evasive action. The physical characteristics of the device and the characteristics of the animal predict the likelihood of it being within the swept area of the turbine, while the ability of the animal to take evasive action predicts the probability of a collision occurring if the animal is in the swept area. There is a distinction in spatial scale between the two processes. It is important to highlight that although the distinction in spatial scale is evident, there is also a distinction in the behavioral processes likely to be influencing the responses involved. Avoidance will influence the probability of encounter, but evasion will influence the probability of strike.

The next step in understanding collision risk is to determine how many mortality events are expected to result from a predicted number of collisions. This involves the relationship between a range of strike variables (e.g., the blade speed at the time of impact, what part of the animal's body is struck, and which part of the blade struck the animal) and the probability of mortality resulting from these conditions.

Finally, the framework links the predictions of individual-level mortality with the predicted population consequences for a population unit, providing estimates of potential damage that could be incurred by sensitive populations.

In the future, it may be possible to incorporate an assessment of sublethal effects of collision resulting in injury to an animal but not death. Achieving this addition to the model will require understanding the effect of likely injuries sustained, as well as the probability that an injured animal will survive and reproduce following an injury.

The best understood processes in this framework are those related to the prediction of the likelihood of a collision and resulting collision rate estimates for a given scenario or device. However, there is a general lack of empirical understanding of avoidance and evasion behaviors in marine animals, which decreases our understanding of the likelihood of collision events. There is also a general lack of understanding of the consequences of collisions. As we learn more about the animals' behavior around devices and the consequences of collisions, modeling the outcomes and relating those individual outcomes to the population will become straightforward, as long as we know the status of the population of concern, including the size of the population, age- and sex-specific survival and reproductive rates, and the degree of density dependence in the population (density-dependent processes occur when the population growth rate

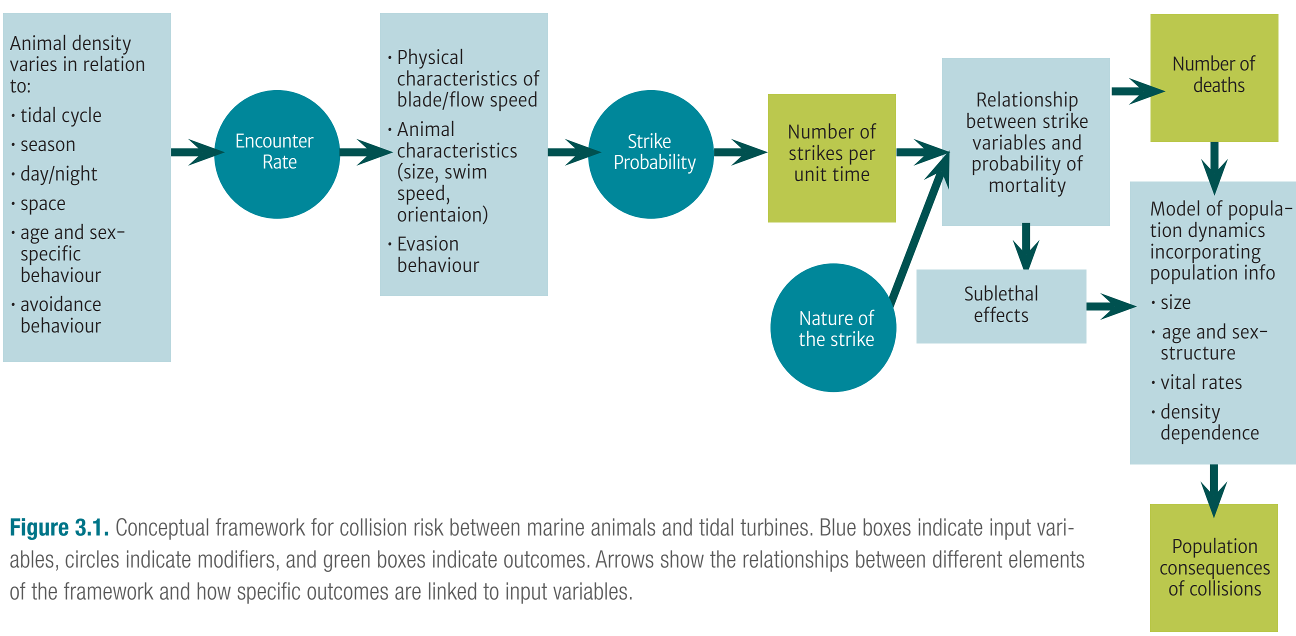


Figure 3.1. Conceptual framework for collision risk between marine animals and tidal turbines. Blue boxes indicate input variables, circles indicate modifiers, and green boxes indicate outcomes. Arrows show the relationships between different elements of the framework and how specific outcomes are linked to input variables.

is dependent on the density of the population). It would also be useful to understand the age- and sex-specific collision rates because it is likely that not all portions of the population are equally at risk.

Each regulatory jurisdiction is likely to have a preferred mechanism for determining effects on populations, based on observations and data for individuals or small groups of animals. The mechanisms for understanding population effects will differ between marine mammals, fish, and seabirds; particularly when addressing the combined likely effects of multiple projects acting upon the same same bio-geographical populations of marine animals and birds. However, a set of common models or a framework could help move the MRE industry forward worldwide.

3.4 MARINE MAMMALS

Marine mammals are considered to be one of the groups potentially in danger from collision with tidal turbines, and most jurisdictions afford them a high level of legal protection.

3.4.1 SUMMARY OF KNOWLEDGE THROUGH 2012

The Annex IV 2013 report Environmental Effects of Marine Energy Development around the World (Copping et al. 2013) provided a summary of the current state of knowledge of the interaction of marine animals with turbine blades. In it, information from a chosen set of verifiable sources was compiled and compared among projects and research studies. Gaps in information that hindered further analysis or interpretation were identified.

The goal of the 2013 report was to examine and evaluate the comparability and applicability of the information collected to determine likely interactions between marine animals and tidal turbines. Laboratory flume and tank studies were also examined in the report; however, none of these have been carried out on marine mammals because of regulatory prohibitions on experimenting on higher life forms. Such experiments have only been carried out on fish and certain invertebrates.

Key sources of information that proved to be the most useful were direct measurements such as visual or passive acoustic recordings. To date, these measurements have been taken around small-scale devices and/or single devices. There was limited availability of these data because of the low number of devices in use, and because of the fast-flowing, turbid, and dark conditions where devices are deployed make these data difficult to collect. Examples of these data were examined in the report.

Numerical models that have been developed to predict interactions of marine mammals with turbines were also examined. The low level of data from the real environment was found to be the key limiting factor of these numerical models because they require such data in order to be validated. Specifically in relation to marine mammals, there is a lack of reliable data related to key behaviors and populations, which limits the robustness of numerical models.

Direct observations of marine mammals were made at Marine Current Turbines' (MCT's) SeaGen in Strangford Lough, Northern Ireland, and at OpenHydro's open-center turbine at the European Marine Energy Centre (EMEC), Orkney, Scotland.

At SeaGen, monitoring commenced four years prior to and continued three years after the installation of the facility. This included aerial and shore-based surveys of marine mammals and seabirds; aerial, satellite, and boat surveys to follow telemetry data from tags placed on selected individual seals; passive acoustic monitoring for harbor porpoise clicks; and monitoring of underwater turbine noise from a device mounted on the pile holding the turbine. The monitoring program showed no major impacts on marine mammals from the tidal turbine. There was minor displacement of marine mammals; seals avoided the center of the channel when the turbine was operating and harbor porpoises were temporarily displaced from the area during construction. Mitigation measures meant that the device was shut down when marine mammals were detected within 30 m of the device, so there was no potential for observing direct interaction of the animals with the turbine blades during the monitoring period.

Video footage was collected around Open Hydro's open-center turbine. No direct interactions between marine mammals and turbines were observed, and there were frequent observations of marine mammals (seals, porpoises, and small whales) around the turbine.

Two collision risk models were examined as part of the report and directly relate to marine mammal interactions with tidal turbines. The models analyzed the encounter rate and the consequences of encounter, respectively. Both models relied upon significant assumptions, which limited their applicability to other sites..

A model developed at Scottish Association for Marine Science (SAMS) predicts the collision risk for fish, diving birds, and harbor porpoise. The model was developed to estimate the potential encounter rate between both herring and harbor porpoise and a hypothetical array of 100 tidal turbines. The model predicted that 10% of Scotland's harbor porpoise population would encounter the array each year. It was acknowledged that the model had a number of limitations caused by assumptions such as that animals are evenly distributed and that they do not engage in evasive behavior. This model only predicts encounters each of which does not necessarily indicate a collision.

PNNL and Sandia National Laboratories (SNL) developed a model that estimates the consequences of encounters between animals and turbines. It estimates the damage to the head region of a Southern Resident killer whale caused by a strike from an OpenHydro open-center turbine. The model showed that the encounter would almost certainly not be fatal. However, a number of limitations were acknowledged in the study including that many aspects of the whale's behavior were not considered. In addition, detailed information about the strength of the specific whale tissues was not fully accounted for in the model.

Although limited data were collected from these studies, it has been acknowledged that there is little reason for fish or other animals to remain in high-speed tidal currents because the bioenergetic cost of maintaining their position is high, even though the potential for refuge and foraging opportunities may cause some animals to remain in the lee of the turbine. However, often these areas are important channels for migration or moving between feeding, breeding, or resting grounds. Therefore, avoidance or evasion measures may have long-term effects on populations and ecosystems, because fewer members of the population will be injured or killed by turbines.

To date, data about larger installations have not been gathered. It was acknowledged in the Annex IV 2013 report that it will be essential to closely monitor the interactions with large arrays as they are installed in the future. Current models will have to be validated with field data in order to improve their accuracy and allow them to be relied upon in field situations.

3.4.2 KNOWLEDGE GENERATED SINCE 2013

Since the publication of the previous Annex IV report (Copping et al. 2013), very little additional data from studies monitoring marine mammals around tidal turbines have become available.

The monitoring at SeaGen was detailed in the 2013 report and there has been little change since then. However, some data collected during the period covered by the 2013 report has been analyzed further to understand seal-turbine encounter rates and to quantify potential avoidance behavior by the seals (as indicated below). The shutdown mitigation at SeaGen is still in place, so there have been limited opportunities to further understand collision risk. Progress was made in 2013 and 2014 to move toward a trial removal of the mitigation step with associated close-range monitoring of seals around the device. However, technical issues encountered by Siemens prior to the installation of the monitoring instruments delayed the project and the subsequent announcement regarding Siemens' divestment of the MCT business meant that the trial did not progress as planned, despite having obtained consent from the regulator. The data collected by sonar during the operation period 2010-2013 (and other aspects of the monitoring program) were used in a risk assessment conducted to demonstrate that a short period of unmitigated operation would not have a significant impact on the harbor seal population. This is a good example of adaptive management, where post-consent monitoring provided the data required to progress toward a relaxation of monitoring requirements as additional information was gathered.

Several other developers have implemented nearfield monitoring around test deployments with the objective of monitoring marine mammal (and other marine animal) interactions, but very little detail has entered the public domain. Monitoring summaries from various developers deploying devices at the EMEC test center indicate several examples of video cameras and strain gauges on blades aimed at detecting the blow from a marine mammal collision. Varying levels of success have been reported, for example as part of the ReDAPT (Reliable Data Acquisition Platform for Testing) project monitoring the Alstom turbine, where the poor lighting levels and turbid flow meant that the camera was not a viable monitoring tool. In addition, several issues were encountered with camera operation and cable connection (Harrison 2015). As part of the ReDAPT project, algorithms had been developed to monitor spikes in the strain gauges, assuming that a spike may indicate a collision with a large object in the water such as a marine mammal. The approach taken on this project was to only interrogate the strain gauge data when data from EMEC wildlife monitoring (shore-based marine mammal observations) indicated a sighting of a marine mammal at the surface in the vicinity of the device. No such sightings took place during the operation of the device and this led to the conclusion that there was very little marine mammal activity in the area of the turbine and that marine mammals are likely to be avoiding the turbine.

An Atlantis AR1000 turbine was instrumented at EMEC with a combination of strain gauges and a video camera was installed to monitor potential collision risk events. However, the brief operating periods did not provide the research team with sufficient time to calibrate the collision monitoring system. As a result, Atlantis was unable to gain any collision monitoring information from the turbine (Xodus, Aurora 2010; *http://www.gov.scot/Resource/0046/00463638.pdf*).

A Scotrenewables device was instrumented in 2010 with a camera and a hydrophone to assess potential collisions with the device and strain gauges were added in 2011. After October 2012, when the device was independently operating for long periods, marine mammal surveys were conducted using underwater camera footage and hydrophone data (Scotrenewables Tidal Power Ltd. 2010).

Monitoring of the Voith Hydro Hytide device at EMEC used video and strain gauge technology to monitor collisions. Initially, all three cameras provided clear images when the turbine was at standstill and when it was in operation. Fish and jellyfish were spotted as well as a single diving bird; the organisms were all relatively close to the camera and clearly identifiable. Fish could not be identified to a more specific level than just "fish." Organisms farther away from the camera were difficult to identify. After a month in the water, fouling obstructed the view of two of the cameras. In terms of strain gauge data, vast volumes of data and the high number of "spikes" produced each day by the strain gauge apparently made analysis of these data difficult and no further information has been provided (Aquatera Ltd. 2011).

Marine mammal observations at the Cobscook Bay Tidal Energy Project made by trained Ocean Renewable Power Company (ORPC) personnel in 2013, during periods of operation, maintenance, and retrieval, indicated no changes in marine mammal presence or behavior in the vicinity of the project. ORPC reported no evidence of marine mammal strike with system components during deployment and retrieval or with turbine generator unit foils during operation, although it is unclear from monitoring reports how this was determined (ORPC 2014).

The EMEC carries out land-based vantage-point surface wildlife observations at its four test sites in the Orkney Islands. Although the main objective was to provide baseline data that can be used to look at the distribution and behavior of marine mammals, diving birds, and other wildlife based on the potential for any displacement effect, the data can also be used to inform individual collision risk assessments at EMEC.

A number of projects (described below) are in various stages of development and will involve monitoring marine mammals in close range around tidal turbines to provide information to improve our understanding of collision risk.

3.4.2.1
MEYGEN INNER SOUND

Phase 1 of the MeyGen project involves the deployment of up to six turbines in the Inner Sound, Pentland Firth, Scotland. The decision to grant a Marine License to the project included the stipulation that "the impacts of which will be monitored in full before the Scottish Ministers may agree to any further future stages of the Development being deployed." A condition of the consent is that monitoring be implemented for "Collision/encounter interactions with the tidal turbines for diving birds, marine mammals and fish of conservation concern." A particular concern for this development is the status of the Orkney and Pentland Firth harbor seal population, which has been declining significantly (SCOS 2014). The detailed nature of this monitoring has yet to be determined but is likely to incorporate active sonar monitoring of fish and marine mammals around a turbine along with an array of hydrophones to enable three-dimensional (3D) passive acoustic monitoring of echolocating cetaceans. MeyGen is working with the Sea Mammal Research Unit at the University of St. Andrews as part of the Scottish Government's "Demonstration Strategy Project: Trialling Methods for Tracking the Fine-Scale Underwater Movements of Marine Mammals in Areas of Marine Renewable Energy Development."

MeyGen is also working on environmental monitoring with the University of Aberdeen as part of a Knowledge Transfer Partnership. This collaboration will involve the deployment of the FLOWBEC platform (Williamson et al. 2015)—a self-contained subsea platform for acoustic monitoring of the marine environment around marine energy devices. The first turbines will be deployed in spring 2016.

3.4.2.2
DELTASTREAM, RAMSEY SOUND

Tidal Energy Ltd (TEL) installed its testing DeltaStreamTM, a full-scale tidal-stream generator, in Ramsey Sound, Pembrokeshire, UK in December 2015. Similar to the MeyGen project, a condition of the license granted to TEL is that an environmental monitoring program be implemented to understand the potential collision risk the device poses to marine mammals. Harbor porpoises and grey seals are frequently present in Ramsey Sound, and the development site is within a Special Area of Conservation, designated under the European Habitats Directive for the protection of the breeding grey seal population found there. The monitoring associated with the DeltaStream device includes an array of 12 hydrophones deployed on the device itself, capable of detecting and tracking echolocating porpoises in near real time, and a multibeam sonar to detect and track marine mammals on approach to and immediately around the rotors. TEL will also be trialling collision detection technology by way of accelerometers and strain gauges on the rotors (Bromley et al. in press).

3.4.2.3
FORCE TEST CENTRE, NOVA SCOTIA

There are currently no plans to carry out nearfield monitoring for collisions at the FORCE Test Centre, although individual berth holders may be developing their own plans that are currently not publicly available.

3.4.2.4
FUNDY TIDAL INC.

Fundy Tidal is in the process of developing passive and active acoustic monitoring plans and a marine observer program to study the potential effects of its pipeline for tidal energy developments on marine mammals and birds. More details and results of the Environmental Effects Monitoring Programs and associated research and development projects are expected to be available soon.

3.4.3
GUIDANCE ON COLLISION RISK AND MONITORING

The following guidance documents include some information about how data should be collected to inform either predictions of collision risk or to monitor collisions themselves:

- Scottish National Heritage Guidance on Survey and Monitoring in Relation to Marine Renewables Deployments in Scotland Volume 2. Cetaceans and Basking Sharks (*http://www.snh.gov.uk/docs/A585083.pdf*) and Volume 3. Seals (*http://www.snh.gov.uk/docs/A585082.pdf*). This primarily provides guidance on survey methodologies.
- Natural Resources Wales has developed guidance to inform surveying and monitoring of marine mammals at wave and tidal energy sites in Wales (Sparling et al., 2015). This document is targeted at pre-consent application surveys and provides guidance on information requirements and appropriate survey methodologies for an assessment of collision risk at tidal energy projects.
- Scottish Natural Heritage has developed guidance for the prediction of potential collision risk between tidal turbines and marine wildlife (Band 2015). This guidance is currently out for public consultation in draft form (*http://www.snh.gov.uk/planning-and-development/renewable-energy/consultations/*). This guidance contains useful descriptions of three available models used to estimate the number of animals likely to collide with MRE devices, guidance on which approach to choose under a range of circumstances, and guidance on obtaining the information required to run the models. Spreadsheets are also provided for each model alongside detailed notes on how to use each spreadsheet.

3.4.4
BASELINE STUDIES: BEHAVIOR OF MARINE MAMMALS IN TIDAL ENVIRONMENTS

As noted in Section 3.3, the baseline density and behavior of marine mammals in areas where MRE devices are to be installed is an important predictor of collision risk. Therefore, effort in some regions has focused in recent years on understanding baseline use of tidal environments by marine mammals. Benjamins et al. (2015) carried out a comprehensive review of available information about how marine mammals and seabirds use of tidal-stream environments and concluded that foraging opportunities appear to be the main attractor, likely driven by enhanced prey abundance, vulnerability, and/or diversity. Studies to date have generally shown that usage and behavior in tidal areas can be variable and site-specific.

Much of the work on marine mammals in tidal environments has focused on the harbor porpoise. Several studies of harbor porpoise spatial usage of tidal areas have reported higher abundance during periods of high tidal flow (Pierpoint 2008; Marubini et al. 2009: Hall 2011). Embling et al. (2010) reported that maximum tidal current was the best predictor of distribution and that greater numbers are predicted in areas of low current. Conversely, Wilson et al. (2013) investigated harbor porpoise abundance in tidal areas on the west coast of Scotland and concluded that harbor porpoise use turbulent eddies, formed as a result of tidal outflow from the tidal narrows, rather than the tidal narrows themselves. The differences may be a result of the tidal differences in the study areas or due to subtle differences in the analytical methods. A follow-on study found that a number of other environmental covariates were better predictors of porpoise presence over the whole of the Hebrides (Booth et al. 2013).

Recent investigations into fine-scale porpoise density and use of the water column at a variety of tidal sites in Scotland have provided a substantial data set on porpoise depth distribution and underwater behavior in tidal rapids that shows a large degree of variation between sites. These data and the methodological and analytical developments associated with them are summarized by Macaulay et al. (2015a; 2015b). This study showed that the depth distribution of harbor porpoise was typically bimodal with a maxima between 0–5 m and another at 22/24 m, which was similar across sites regardless of differences in seabed depth, thereby providing insight into the potential separation of the porpoise from the depth of a tidal turbine blade. At the only site where measurements were taken at night (Kyle Rhea), porpoises were generally located near the sea surface, highlighting the importance of understanding diurnal variation in depth distribution for accurate prediction of collision risk (Macaulay et al. 2015b).

Monitoring at the FORCE site in Minas Passage, Bay of Fundy, using CPODs and an Open Sea Instrumentation SUB Buoy, demonstrated spatial and seasonal variation in harbor porpoise presence with peaks in the spring and the fall (Wood et al. 2014). Tidal covariates were also important; porpoise presence peaked during moderate flood tides and during moderately high tides. This study also demonstrated that the extreme water flow at tidal turbine sites poses a challenge for monitoring with passive acoustics because the tidal flow noise and bedload transport of moving cobbles and other materials registers on the hydrophones throughout the site. Wood et al. (2014) therefore recommend that preliminary studies be conducted at different locations during extreme tides to identify and avoid locations where excessive flow and bedload noise occur.

Until relatively recently, quantitative studies of pinniped usage in tidal areas were sparse. Studies have suggested a number of relationships between seal activity and tidal patterns, although these are often complicated by haul-out behavior and breeding strategies. The availability of intertidal haul-out sites decreases during flood tides and there is a noticeable geographic variation in the haul-out behavior of seals as a result of the differing tidal regimes (Thompson et al. 1997). Consequently, studies have noted higher seal abundances in narrow channels during flooding tides (e.g., Zamon 2001) and attributed this to foraging behavior. VanParijs et al. (1999) noted the reproductive strategies of harbor seals were spatially and temporally affected by tide cycles; male vocalizations were significantly greater in tidally dominated areas during flood tides. Recently seal-tagging (telemetry) studies have been employed specifically in a number of tidal areas around the UK (Thompson at al. 2012, 2014; Thompson 2013;). These studies are summarized by Sparling, (in press), but the general features of the data sets relevant to collision risk are: 1) a high degree of inter-individual variation, which means that the degree of risk is not equal across all individuals in a population; 2) variation in the local abundance of seals at a number of sites, which indicates that risk varies across the tidal cycle (in addition to variation resulting from changes in flow speed and consequently turbine blade speed); 3) depth distributions being very similar across sites, and benthic diving resulting in a bimodal depth distribution with the majority of time spent either near the surface or at the seabed; and 4) a degree of site-specific variation in the distribution of seals at each site. This latter finding is important because it may limit the degree to which models can be generalized across sites and may require a degree of site-specific information to be gathered to enable a confident prediction of collision risk.

There are few examples of direct quantitative research on the use of tidal habitats for other marine mammal species or in other areas. However, there is some evidence that some species of marine mammals are often associated with tidal habitats (see Benjamins et al. 2015 for a detailed review), but generally little information is available about spatial and temporal variation of marine mammal populations associated with fine-scale tidal features. Many marine mammal species have been shown to display a great deal of behavioral plasticity and intra-specific variability in habitat preference, so it is likely that many marine mammal populations will use high-energy areas throughout their range.

3.4.5 MODELING AND DATA INPUTS

A robust, quantitative assessment of collision risk prior to the deployment of devices is a requirement of the licensing and permitting process in many countries (see Section3.4.6). The general approach has been to use site-specific data to make a prediction of collision risk (see Section 3.3.2). Sparling et al. (2015) provide a detailed review of the information required to inform such predictions, and Band (2015) provides guidance on how to incorporate this information into common modeling approaches. Generally, typical approaches to making these predictions are based on either the abundance of animals in an area generated from a dedicated survey (e.g., Wilson et al. 2007, 2012), or transit rates of animals through the area swept by the turbine rotors (e.g., Davies and Thompson 2011; Band 2014), which may be derived from tagging studies or direct observations, or by converting survey-derived density estimates to transit rates. Transit rates might also be referred to as animal flux through the area. Both of these approaches require information about each species' vertical use of the water column (i.e., the proportion of time animals are spending at the depth of the devices).

Risk of collision will vary across the tidal cycle as a result of variations in rotor speed with current speed, approach velocities of animals, etc., as well as any variation in animal abundance over the tidal cycle. Therefore, understanding the temporal patterns in the likelihood of an animal encountering the device and the risk posed by the device is crucial to an accurate prediction of the likelihood and consequences of a collision. In some areas, varying patterns of abundance of some species have been documented in relation to tidal cycles (e.g., harbor porpoise: Pierpoint 2008; Wilson et al. 2013).

In addition, although this is rarely, if ever, addressed in collision risk assessments, understanding the degree of residency and the rate of individual turnover at a site is potentially important for the interpretation of the significance of current collision risk model outputs. A project at a site that is used by a large number of transient animals passing through will likely pose a different risk than at a project at a site where there is a small resident population, even though a snapshot measurement of density at the site may be the same. For a given prediction of a collision rate, the total number of potential collisions per year expressed as a proportion of the total population of vulnerable animals will be lower with a larger transient population, but the absolute number of animals affected may be much larger over a longer period of time, because animals are essentially "replaced" by new animals coming into the area. Conversely, the opportunities for learning and behavior modification will be highest where there is a small population of resident animals that may encounter devices. Thus, the turnover of individuals at a site will fundamentally affect the number of animals at risk.

Key information is required to allow for robust quantitative predictions of collision risk, as follows:

1. animal flux through the swept area (and how flux varies across the tidal cycle);
2. spatially explicit information about density for each species at the project site (in conjunction with information about use of the water column) can act as a proxy for animal flux information, which often is not possible to collect;
3. the turnover/residency of individuals at the site;
4. avoidance/evasion or attraction rates (and how they may vary with the number and configuration of devices);
5. the consequences of collisions for individuals (i.e., the proportion of collisions that result in mortality or significant effects on the survival and fecundity of individuals);
6. the size of the relevant population management unit for each species and an understanding of the level of acceptable mortality.

Species information (1 - 3 above) can be gathered using site-specific surveying. Avoidance/evasion or attraction information (4 above) could be collected at a site during the operational phase. Data about collision consequences and population management units (5 and 6) are possibly best acquired using a research approach rather than site-specific developer-led monitoring.

It is important to note that, as discussed in Section 3.2.2., any estimates of collision risk are extremely sensitive to assumptions made about the avoidance behavior or evasive abilities of animals. We might expect this to vary between different species, individuals, and device types as well as with site-specific factors such as turbidity, noise levels (ambient and device-generated), and ambient light levels. It is important to note that in the absence of empirical information about avoidance and evasion, a confident quantitative prediction of collision risk will not be possible, regardless of how precise or robust site-specific density estimates are. An important consideration, therefore, is whether to best deploy effort in collecting additional pre-deployment data, refining modeling approaches further, or investing in more in post-installation monitoring.

Conceptually, collision risk models can be split into those that estimate the possibility of a collision occurring and those that predict the consequences of a collision, if one were to occur. The latter models have focused on fish in relation to hydroelectric dams, but one example applies to marine mammals (Carlson et al. 2014). To date, most modeling efforts have been aimed at estimating the possibility of a collision occurring by using either the SRSL model (aka Encounter Risk Model or ERM; Wilson et al. 2007) or a modified Band model (aka collision risk model). Because of slight differences in the use of terminology (e.g., collision vs encounter), these models might give very different outputs. However, the encounter rate calculated from a SRLS model is similar to a collision risk (assuming no avoidance) from a Band model (Band 2014), except that the SRSL model estimates encounters with individual turbine blades, such that a large whale, due to its size, could encounter multiple blades during transit through a turbine. A Band model would count this as a single collision. To avoid confusion, we will refer to these two models as the SRSL and Band models. Band (2015) provides a detailed description of both of these modeling approaches and refers to them as the ERM and CRM models, respectively.

The approaches of the SRSL and Band models are broadly similar in that they both use a physical model of the rotor, the body size, and the swimming activity of the animal to estimate the potential collision rate. The SRSL model focuses on the volume per unit time swept by each blade, while the Band model focuses on the number of animal transits through a rotating rotor and the collision risk during each transit. For both models, an appropriate reduction factor is then applied to make allowance for avoidance.

The SRSL model has its origins in predator-prey models (as applied to the collision between a medusa predator and small fish prey), where the turbine blade is considered a predator and the animal the prey (Wilson et al. 2007). In contrast, the Band model has its origins in estimating collisions between birds and wind turbines (Band 2000). Data inputs to these two models are similar, but some key differences exist as well. Both incorporate basic biological inputs such as animal length and velocity as well as the physical parameters of the turbines themselves (Figure 3.2). The biggest data input difference between the two models is that the SRSL model requires a 3D density estimate of the animals in the vicinity of the turbine, whereas the Band model requires an estimate of the number of animal transits through the turbine-swept area.

Animal density and transit rate are of course related to each other; the higher the density, the higher one would expect the transit rate to be. Band (2014) relates density to transits in the following way:

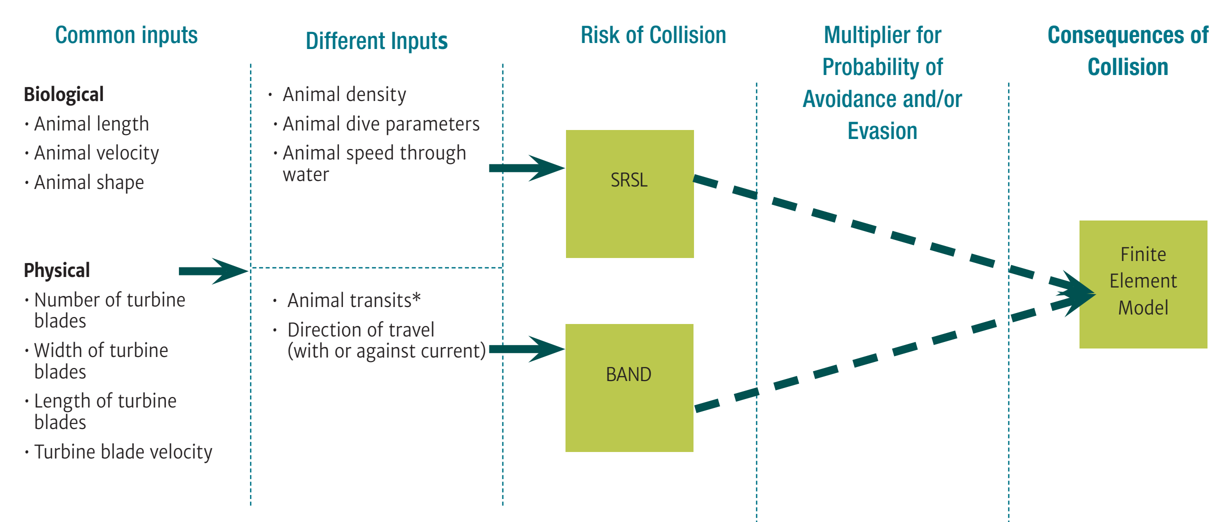
$$\textit{No of transits} = D(\Pi R^2)v$$

The assumption in this equation is that the swimming direction of the animals is random relative to the water, which seems to be an unlikely but necessary assumption for Band (2014) to compare SRSL and Band model outputs. Using the above assumption and standardized inputs, Band (2014) compared the outputs of an SRSL model and Band model at the EMEC tidal site in the Fall of Warness. He found that the Band model outputs were roughly 1.4 times the outputs of the SRSL model for harbor porpoise and seals.

While Band (2014) felt this to be a significant difference in the estimates of collision risk from these two models, two sets of biological inputs to either model are likely to result in much larger differences in collision risk estimates. These could be loosely termed as "habitat use" and "behavioral response." Habitat use includes how, when, how often, and where animals use a specific area. These all affect estimates of animal density and transit rates. Even using more localized estimates of density can have huge effects on model outputs. There was a 37 times greater difference in the encounter rate estimates of harbor porpoise at the EMEC site depending on whether density estimates derived from EMEC observation data were used as opposed to SCANS density estimates (Band 2014), although these density estimates differed greatly in the extent to which corrections for biases related to distance and detectability. Likewise, Thompson et al. (2015) estimated harbor seal collision risk to a proposed tidal turbine array in the Pentland Firth using transit data from tagged seals. These estimates of transits led to collision risk estimates that were six times lower than those based on local uniform density estimates (Batty et al. 2012; Thompson et al. 2015). The point here is that the use of tidal areas by marine mammals, and therefore the potential for collision, is likely to vary significantly with location, depth, time of day, tidal velocity, etc. For a collision to occur, a marine mammal has to be in a very specific location at a specific time. The use of average density, depth, or broad estimates of transits may therefore result in significant under- or over-estimation of collision risk, depending on the specific habitat use in that location.

Another component of habitat use that has not been considered in collision risk models is individual variability. A small subset of the population may use the habitat in a specific way that increases its risk of collision, but the remainder of the population may avoid the area and thus have no risk of collision. Density estimates ignore this individual variability, and tag transit data are difficult to scale up to a population because of the uncertainty of how much individual variability there is in the population and therefore how representative of the larger population these tagged animals are.

As discussed in Section 3.3, the second set of biological inputs to collision risk models (or rather a modifier of their outputs) consists of avoidance, attraction, and evasion. Because so little is known about the potential scale of these inputs, people tend to either not include any estimate of their effect on model outputs (e.g., Wilson et al. 2007) or run the model output through very broad (i.e., 0 to 99% avoidance) assumptions (e.g., Band 2014). Obviously, these different assumptions will have a large effect on estimates of collision risk. Thus, it seems that the choice of model used is of less importance than the biological assumptions or data inputs used in the actual models. According to Band (2015) results should be expressed, as a default, using six avoidance rates: 50%, 90%, 95%, 98%, and 99%. Although the justification for the lower cutoff at 50% is unclear, given the lack of empirical data to inform this,



*Animal transits through the turbine-swept area incorporate animal dive parameters.

Figure 3.2. Depiction of the two main collision risk models, their common and unique data inputs, how avoidance and evasion are incorporated into those models (as multipliers to their outputs), and how these results might then be informed by a consequences of collision model.

applied in this way, the adjustment incorporates the combined effects of avoidance and evasion (as defined in Section 3.2.3 and discussed in Section 3.3) despite the differences between them in mechanistic terms. Although there is currently no information to inform our understanding of the ability of marine mammals to evade collisions at close range, seal telemetry data from the operation of the SeaGen tidal turbine in Strangford Lough suggest a degree of avoidance. Keenan et al. (2011) and Savidge et al. (2013) report that the spatial distribution of seal transits changed during operation of the turbine compared to pre-installation data. Individual tagged seals transited past the turbine on average 20% less when the turbine was operating relative to when it was not rotating. Wood et al. (in press) quantified the change in activity around the turbine site between baseline, installation, and operation periods and concluded that on average there was a reduction in activity of ~66% within 200 m of the turbine. They used data from Strangford Lough to examine the sensitivity of the SRSL model and the Band model to a range of varying input parameters. The single biggest effect on collision risk was avoidance, which is unsurprising considering it is a direct multiplier of risk. The assumed depth distribution had the second largest effect with U-shaped dives, resulting in an overall lower level of risk than V-shaped dives. Harbor seals are seen to engage in U-shaped dives, heading straight for the seabed, spending time at the bottom, and swimming upward toward the surface, rather than V-shaped dives in which the animal does not spend time on the seabed. Given the uniformity in dive distribution patterns observed across seal studies to date, there seems to be little need to gather site-specific dive profiles, so that models can be updated with generic dive distributions, at least in the UK.

It is important to note that most assessments to date have considered single devices or small arrays, and there is uncertainty about how collision risk will scale with the number of devices at a site. It is unlikely to be a simple linear increase due to repeated responses to individual devices and learning by animals encountering multiple devices. The distances over which animals may avoid MRE devices may change with larger arrays (animals avoiding the entire array reducing the probability of encounter with additional devices) because evasive behavior may alter risk (the potential for avoidance of one device taking an animal on a path where encounter with additional devices may be more likely). Therefore, modeling collision risk at array-scale developments requires careful consideration.

The consequences of collision are not generally considered in predictions of risk, with the exception of the work by Carlson et al. (2014), which determined that a Southern Resident killer whale struck by an OpenHydro turbine blade is not likely to experience significant tissue injury (as tested on previously frozen whale carcasses) that is likely to result in death or debilitating injury. The resulting blade impact forces calculated appear to be sufficient to cause some subcutaneous damage to the whale, while laceration of the skin is thought to be somewhat unlikely. Estimated impact force was insufficient to damage the orca (killer whale) jawbone. This approach is now being applied to understanding the potential consequences for other marine mammal species of a strike by a "typical" horizontal-axis tidal turbine.

A recent project at the Sea Mammal Research Unit (SMRU) has taken an empirical approach to this issue; researchers have carried out a series of trials of "collisions" between rotors and seal carcasses at a range of speeds to understand the degree to which damage occurs (Thompson et al. 2015). The blade profile chosen represented a section near the tip where it is narrowest/sharpest and therefore most potentially damaging. The blade profile was attached to the keel of a jet drive boat to simulate the leading edge of a turbine blade. The boat was driven at and collided with a number of previously frozen grey seal carcasses at a range of effective speeds from 1.95 m/s to 5.32 m/s. Resulting injuries were assessed via inspection of radiographs and by detailed post-mortem analysis. These data and the estimates of effective collision speeds were used to assess the likelihood of injury or death in real collisions. Post-trial x-rays and post-mortem analysis revealed no evidence of skeletal trauma. Neither were there obvious indicators of trauma such as tears, avulsions, or ruptures in the integument, musculature, or organs, in any of the test subjects as a result of the collision trials. However, due to the difficulties in assessing soft-tissue damage such as bruising and tissue edema in previously frozen carcasses, these soft-tissue assessments were not considered reliable indicators of trauma in this experiment. The results of the trials suggest that slow speed collisions with the tips of tidal turbines, at less than the maximum 5.32 m/s measured in this test, are unlikely to produce serious or fatal injuries in grey seals. It seems likely that a significant proportion of impacts would not be fatal, given the range of speeds tested in this setup. These are, however, preliminary results and should be treated with caution because they are limited in their inability to assess soft-tissue damage or to determine potential unconsciousness as a result of blunt cranial trauma or the consequences of collisions at speeds above 5.32 m/s. Maximum rotor tip speed for existing turbine systems are approximately 12 m/s, but Thompson et al. (2015) present a histogram of estimated blade speeds during collisions with randomly moving seals and conclude that most collisions would be with slowly moving blades. This takes into account the following:

- The speed of any particular point on the blade will be linearly related to the distance from the center of rotation being close to zero at the center even at high rotation rates.
- In the absence of other information, the available CRMs assume that marine mammals will not react to the presence of a turbine. Therefore, it is assumed that the impact point will be at some random point on the blade.
- The probability of collision with any particular section of the blade is equal to the proportion of the total swept area that is swept by that blade section, and related to the distances from the center (e.g., the outer 10% of the blade sweeps 19% of the total area, while the inner 10% sweeps only 1%).

Under these assumptions, the fastest blade speed observed in the collision trials carried out by Thompson et al. (2015) (5.2 m/s) would be expected to be faster than 67% of collision speeds in random collisions with turbines. Therefore, under these assumptions, we could conclude that at least two-thirds of actual collisions are unlikely to be fatal. It should be noted that these collision speeds are based on random collision rates of an animal and a turbine, which is an assumption unlikely to hold true in the real world.

Using the outputs from these (and similar) studies (by PNNL and SMRU), it is possible that the relationship between rotor speed and the probability of mortality can be estimated and this parameter included in collision risk models. Therefore, there is also scope to integrate assumptions about relative risk within current predictive models, and place due weight on periods of low rotor speed and the proximity to the rotor hub of encounters, when the risk of death or serious injury may be low.

An ongoing Marine Scotland project aims to assess the effects of tidal, diurnal, and seasonal variations on the likelihood of seals being present in areas of expected tidal development, and the likelihood that seals would suffer a fatal injury as a result of an encounter. Results will be used to update available current encounter risk models to reflect the newly gained understanding.

There are no examples of collision risk modeling approaches for marine mammals that have been directly linked to a model to determine the population consequences of a given predicted level of mortality, although a model has developed for diving birds—the "exposure time approach" (Grant et al. 2014). This model avoids attempting any quantitative assessment of collision risk for individual animals passing through turbines, or avoiding them, but estimates the minimum collision rate required to have a damaging effect on species populations. A similar approach could be developed for marine mammals, and by extension, by using a "reverse engineering" principle one could calculate the level of density that would be required to achieve that minimum collision rate.

Predictive models generally output a single point estimate for each scenario. Given the uncertainty surrounding the assumptions that have to be made, models should also have the ability to incorporate the uncertainty in input parameters and provide a confidence interval for the point estimate.

3.4.6
IMPACT ASSESSMENT

In most countries, environmental impact assessment legislation requires a detailed assessment of the risk of developments on habitats and species, with a particular focus on species and habitats protected by national and international legislation.

In Europe the main driver of relevance to collision risk is the Habitats Directive, through which seals and some cetaceans are given protection via protected areas designated under Annex II and all cetaceans are afforded European Protected Species status under Annex IV.

In the UK, this legislation is transposed into national legislation, which requires detailed assessment of the effects of MRE projects on protected marine mammal populations. Typically, this assessment involves a quantitative prediction of collision risk using the kinds of models outlined in the previous section. The resulting rate of potential encounters per year is assessed in the context of legislative requirements for that particular species and population; this is generally done in the context of the level of mortality that would not be considered significant for that population. For assessment purposes, model outputs are interpreted in a precautionary manner, whereby encounters are assumed to represent collisions, which are assumed to represent mortalities.

A variety of methods can be employed to understand the potential consequences for a given level of predicted collision mortality. For example, a Potential Biological Removal (PBR, Wade 1998) approach can be taken. In 2010, the Scottish Government introduced the use of PBR to determine the number of seals that could be removed under license from regional management areas without affecting the long-term status of the population. In 2010, the UK Department of Energy and Climate Change (DECC), based on advice from the Countryside Council for Wales (CCW), now Natural Resources Wales (NRW), set thresholds for collision-related mortality at the DeltaStream project using a PBR approach. Similarly, the Northern Ireland regulator used a PBR-based approach to license the removal of the shutdown mitigation at the SeaGen tidal turbine. (See Section 3.2.4. for further details on these case studies).

Alternatives to the PBR approach are stochastic population models (such as the PVA [population viability analysis] approach used to assess avian collision risk with wind turbines). The Interim Population Consequences of Disturbance (PCoD) framework (Harwood et al. 2014; King et al. 2015), which provides a stochastic population modeling approach, was originally developed to assess impacts associated with exposure to underwater noise as a consequence of offshore wind farm construction, but can be adapted to help assess the population consequences of mortality resulting from collision with tidal devices.

3.4.7
ADAPTIVE MANAGEMENT AND MITIGATION MEASURES

Given the continuing uncertainty surrounding collision risk, adaptive management of one form or another is likely to be the only approach possible to allow progress. Below we have detailed specific case studies of adaptive management approaches that have been applied to various consented projects.

SeaGen, Strangford Lough, Northern Ireland. Originally the turbine at this site was shut down when a marine mammal approached it. An Environmental Monitoring and Adaptive Management Plan has been in place since 2006. In 2013, MCT applied for a license trial removal of the shutdown clause. Modeling based on empirical data collected during operation of the turbine by the sonars in place for mitigation, coupled with an analysis of seal telemetry data, suggested that a short trial period removing the shutdown would not introduce any risk to the local harbor seal population. So a short trial was licensed on the condition that enhanced monitoring was put in place to monitor the nearfield fine-scale behavior of seals close to the turbine rotors. The divestment of MCT by Siemens put a hold on plans for this trial and the future of this project is currently uncertain.

Tidal Energy Ltd's DeltaStream in Ramsey Sound, Pembrokeshire, Wales, UK. This single device was approved based on a "threshold" approach whereby collisions must not breach species-specific thresholds. These thresholds were based on an assessment of the current status of the relevant Welsh marine mammal populations and a PBR-type approach (DECC and CCW 2011). The license for the project therefore carries with it the need for the ability to detect and identify (to species) collisions with marine mammals. A detailed Collision Monitoring and Adaptive Management Plan has been developed to ensure that the conditions of the license are met. The monitoring planned for this project to meet these conditions includes monitoring of collision signals from accelerometers and strain gauges on the rotors, passive acoustic monitoring of echolocating porpoises and dolphins around the device, as well as active acoustic monitoring of the area immediately around the turbine blades using a multibeam sonar. The ability to physically detect collisions remains untested. The DeltaStream device was successfully deployed in December 2015.

MeyGen, Inner Sound, Pentland Firth. The first phase of a 398 MW deployment of tidal-stream turbines has been approved. The license for the first phase allows for up to six turbines. The exact details of the operational monitoring and adaptive management requirements are currently being developed, but the license conditions specifically require the development of a Project Environmental Monitoring Programme, which seeks to inform our understanding of the reliability of the collision risk modeling that was carried out as part of the Environmental Impact Assessment (EIA) and to inform the conduct of future turbine deployments. Any approval of subsequent stages was recommended on the condition that information from the monitoring program be used to validate the model and inform further assessments, particularly with respect to collision risk to the regional harbor seal population, which has been undergoing large declines—75% since 2000 (SCOS 2013).

ORPC, Cobscook Bay Maine. Although not specifically focused on marine mammal collision risk, the monitoring program associated with this project has allowed the developer and the regulator to come to consensus regarding the lack of environmental impacts and allowed the developer to reduce the frequency of monitoring surveys based on the increased knowledge of species present and environmental effects. Specifically, as a result of knowledge gained during 2012 project installation and operation, the concurrence of the project's Adaptive Management Plan, and a license order from the Federal Energy Regulatory Commission, ORPC transitioned from dedicated to incidental marine mammal observations for the project in 2013.

At this time, the approach to operational monitoring and the adaptive management requirements for various North American projects (Cape Sharp Tidal, Black Rock Tidal, Fundy Tidal's Grand Passage, Digby Gut) are unknown.

3.4.8 METHODOLOGIES AND INSTRUMENTS

Table 3.2 lists methodologies and instruments used to understand the issue of collision risk between marine mammals and MRE devices. This table includes details of instruments currently in development for this application as well as examples of technology that has been deployed to understand baseline marine mammal use of a tidal habitat; however, few examples exist for monitoring around a tidal device.

3.4.9 CRITICAL UNCERTAINTIES

In general terms, the picture has not changed much since the publication of the 2013 Annev IV report. The significant gaps in data identified by Copping et al. (2013) largely remain. There is still no evidence that direct interactions will cause harm to individuals or populations.

Although advances have been made on the modeling front, and several modeling approaches are well documented alongside guidance for their use, empirical data describing the behavior of marine mammals around operational tidal turbines is still lacking. In particular, the lack of observations and measurements of animal movement around tidal turbines of varying designs that are deployed in multiple waterbodies continues to limit the evidence needed to understand and predict how devices might affect animals in new project locations. Our understanding of the ability of animals to avoid collisions is the single biggest uncertainty of predictive models and has the ability to scale current outputs of collision risk models both upwards (if attraction is an issue) and downwards (if avoidance is an issue).

Table 3.2. Methodologies and instruments applied to date (primarily since 2013) to understand marine animal collision with, strike by, and evasion and avoidance of MRE devices.

Site	Device	Metric	Method/Tools	Reference
FORCE Site, Minas Passage, Nova Scotia	No turbine present	Baseline presence of harbor porpoise	CPODs, Open Sea Instrumentation SUB Buoys with iCListen HF hydrophones[a]	Wood et al. 2013 Benjamins et al. (in prep.).
EMEC, Orkney, Scotland	Atlantis AR1000/Open gravity base structure	Presence, behavior, and depth distribution of marine life (not specifically focused on marine mammals but capable of detection)	FLOWBEC – upward-facing Imaginex Delta T multibeam sonar[b]	Williamson et al. 2015
EMEC, Orkney, Scotland	Alstom turbine	Presence of marine mammals and collision events	Camera and strain gauge monitoring – (part of ReDAPT project)	Harrison 2015
EMEC, Orkney, Scotland	Atlantis AR100	Presence of marine mammals and collision events	Camera and strain gauge monitoring	Xodus Aurora 2010
EMEC, Orkney, Scotland	Scotrenewables	Presence of marine mammals and collision events	Camera and strain gauge monitoring	Scotrenewables Tidal Power Ltd. 2010
EMEC, Orkney, Scotland	Voith Hydro Hytide	Presence of marine mammals and collision events	Camera and strain gauge monitoring	Aquatera Ltd. 2011
Strangford Lough, Northern Ireland	SeaGen	Nearfield encounter rate of marine mammals	720 kHz multibeam sonar (Tritech Gemini)[c]	Hastie 2013
Corryvreckan, Sound of Islay, Kyle Rhea, Orkney, (all Scotland)	No turbines present	Density and depth distribution of harbor porpoises	Vertical hydrophone array	Macaulay et al. 2015
Sound of Islay, Kyle Rhea (Scotland)	No turbine present	Fine-scale distribution of harbor porpoises	Drifting CPODs[d]	Wilson et al. 2014
Kyle Rhea, Pentland Firth, (Scotland)	No turbine present	Fine-scale behavior and depth distribution of harbor seals	GPS GSM[e] tags	Thompson 2013, 2014
Bardsey Is, Ramsey Is (Wales)	No turbine present	Fine-scale behavior and depth distribution of juvenile grey seals	GPS GSM tags	Thompson 2012
Ramsey Sound, Wales	DeltaStream™ (deployed in December 2015)	Close-range encounter rate and fine-scale behavior of seals and echolocating cetaceans	12 channel hydrophone array with PAMGuard module for real-time detection and tracking, Multibeam sonar (Tritech Gemini)	Bromley et al. in press.
In test phase at University of Washington – not yet deployed	No turbine	Encounter rate and fine-scale behavior of marine animals	Integrated instrumentation package including stereo-optical camera, Blue View "acoustical camera," icListen HF hydrophone array, CPOD	Polagye et al. 2014

(a) *http://oceansonics.com/iclisten-smart-hydrophones/*

(b) *http://www.imagenex.com/html/delta_t.html*

(c) *http://www.tritech.co.uk/product/gemini-720i-300m-multibeam-imaging-sonar*

(d) *http://www.chelonia.co.uk/products.htm*

(e) **Sea Mammal Research Unit tags** *http://www.smru.st-andrews.ac.uk/Instrumentation/GPSPhoneTag/*

The collision risk issue has to be dealt with successfully at the small array scale. Any continuing uncertainty will make it very difficult to approve large-scale projects without commitment to potentially expensive and onerous monitoring and mitigation. Although scaling up from single devices to small arrays is complicated by the uncertainties related to how animals might respond to multiple devices, it is unlikely risk will scale in a simple linear fashion with the number of devices. Very little is known about how animals may react to the presence of larger numbers of devices, any view of actual collision risk at the commercial array scale will require a number of assumptions to be made.

If empirical data at the small array scale suggest that collisions are likely to happen at a significant level, the industry will need time for and investment in the development of mitigation. In this instance there will be an urgent need for appropriate and cost-effective mitigation solutions and given the timescale required to research, develop, and approve appropriate methodologies, options should be investigated before clarity can be achieved about the need for mitigation. While several examples are provided in this chapter (Section 3.4.2) of where empirical data are likely to become available in the future to inform our estimation of marine mammal collision risk, many more projects are in the consenting pipeline and require regulatory decision-making before the outcomes of these studies are available. Further refinement of Band model approaches may be the key to giving consent to the early projects while this uncertainty remains. This is possibly best done by achieving a better understanding of site-specific encounter rates, integrating over tidal cycles, and incorporating a variable mortality probability derived from studies such as those of Carlson et al. (2014) and Thompson et al. (2015). Understanding the consequences of collision for individuals is also an important uncertainty. At the moment assessments make the assumption that every collision is fatal, whereas recent work by Carlson et al. (2014) and Thompson et al. (2015) suggests that this is extremely precautionary and that a large proportion of collisions may not result in significant injury. There is an urgent need for further understanding of this issue.

Although a critical gap, data about animal behavior close to turbines and avoidance and evasion capabilities are not all that is required. We also need the ability to determine whether collisions are actually happening. The ability to detect collisions could be very important in understanding collision risk. There is a need for developers to "prove the negative" with respect to collisions between tidal turbines and animals. Current monitoring approaches lack the resolution to be able to actually determine whether or not collisions have taken place. Numerous methods have been suggested but none has yet been demonstrated to actually work. Underwater cameras, for instance, are unable to document a collision in darkness or turbid water, although they may be used retrospectively in combination with sonar in determining what it was that made contact. Passive and active sonar techniques provide information about animals in proximity to a device, but cannot detect physical contact between animals and turbines. Blade-mounted sensors may provide answers, though how effective these would be has not yet been established. The Innovation Centre for Sensor and Imaging Systems is currently reviewing the available data and technology related to this issue (*http://censis.org.uk/*).

3.4.10 LESSONS LEARNED

The state of the science for marine mammal collision risk is still very much in its infancy. However, a number of key lessons are gained from research and experience in the tidal industry since publication of the Annex IV report (Copping et al. 2013) that should be considered when focusing future effort. Experience to date has shown that requiring shutdown mitigation to remove the risk of collision results in the loss of any opportunity for learning about how animals respond to operating tidal turbines and therefore what the real collision risks are. Where devices have been allowed to operate without shutdown mitigation, the monitoring has often not been in place, has not successfully ruled out collision risk, or has not acquired useful information about avoidance or evasion behavior. Experience from several developers operating single devices at test centers has shown that collision detection and video monitoring of devices using underwater cameras is challenging. Monitoring programs for collision risk will require input from technology specialists, biologists, engineers, developers, and regulators to ensure that the critical information is gathered over adequate time frames.

Adaptive management approaches implemented based on a threshold of acceptable impact at the population level require the ability to definitively determine whether collisions are actually taking place. It is doubtful that current nearfield detection and monitoring technologies will be able to actually determine actual collision rates and there is a danger that interpretations of the data will be precautionary; i.e., close-range encounters may be considered collisions. Experience to date (e.g., during the development of the DeltaStreamTM device, Bromley et al. [in press]) has also shown that the integration of nearfield monitoring systems into turbine operation and maintenance can be complex and time consuming, therefore turbine and project engineers should engage with those leading the efforts to develop environmental monitoring as early as possible. Tidal environments are hard on monitoring equipment, so cable and connector designs have to be as robust as possible.

3.4.11 RECOMMENDATIONS

Progress on understanding of the potential risk posed to marine mammals by collisions with MRE devices has been slow. Based on the critical uncertainties and lessons learned highlighted above, we have identified a number of areas as priorities across the broad themes of research; monitoring and development of instruments; and monitoring and mitigation. It is important to note, however, that the distinctions among these categories are not always clear.

3.4.11.1 PRIORITIES FOR RESEARCH

The consequence of collisions for individual animals has been identified as a key uncertainty. Future work should focus on modeling the likely biomechanical impacts and consequences for tissues, over the range of impacts likely to be experienced for the most common turbine designs, with the species most likely to be exposed. Experimental work should focus on further strike studies on fresh carcasses to understand the physical consequences of collisions for tissue and skeletal structures. These studies should involve pathologists as well as biologists and engineers.

Research should also seek to understand the spatial and temporal variation in the baseline use of tidal-stream areas by marine mammals. The degree of variability between sites and among species and individuals, and the dependence of collision risk on these factors, has highlighted the need for site-specific understanding of fine-scale habitat use for a larger number of species and sites than is currently available. Much effort in the UK has focused on harbor porpoises and harbor seals; there is a need to reach a similar degree of understanding for other species in other areas earmarked for tidal development.

Research is also needed to better understand the close-range behavior of marine mammals around operating devices; this should be a key component of any strategic monitoring efforts. The technological limitations of the available methods and equipment to examine close-range behavior, and the need for statistical power that exceeds current capabilities at most sites, make this research challenging for individual project developers to achieve successfully. Strategic coordinated research, led by experienced experts, applied at a number of key specific sites (chosen for their tractability and reasonable encounter rates) is likely to be the best route to success. Documenting and quantifying this close-range behavior will likely require further development of equipment and technology (see Section 3.4.11.3).

There is also a need to develop and refine models that are currently available to predict collision risk for future projects; this will become increasingly more important as additional empirical data become available from research studies and from monitoring for baseline conditions and around operating devices. Driven by the uncertainty inherent in collision risk models, the uncertainty in input parameters needs to be incorporated to provide a confidence interval for the point estimate.

There is only one method available to link collision risk to population-level assessment (Grant et al. 2014), and more are needed. With the exception of the "exposure time approach," current collision models do not extend to consideration of the population consequences of collision. While a range of tools and methods are available (e.g., PBR and other take-based methods, PVA and other stochastic population modeling approaches) they have not often been applied to understanding collision risk around MRE devices. It would be useful to compare all of the currently available approaches for setting limits of acceptable decline of marine mammal populations which could be used to interpret the outputs of collision risk models so that regulators, developers and researchers can determine which is best to use, if any.

There is a need to understand how animals might respond to multiple objects in the water, as the industry scales from single devices to commercial-sized arrays. Unlike single device interactions, it will be impossible to tackle this issue through a "deploy and monitor" approach, coupled with a strong adaptive management approach. However, novel and imaginative approaches are needed.

3.4.11.2
PRIORITIES FOR MONITORING AT FUTURE TIDAL ENERGY SITES

Gathering empirical data at future sites is incredibly important, but the expected rarity of collision events requires that we focus effort on sites with reasonable predicted encounter rates so that monitoring programs will have the statistical power to rule out impacts. Monitoring at sites with low power may be important to verify site-specific conditions, but it will not be very useful for generating data for predicting impacts at new sites. It is important that project monitoring requirements not be generically prescriptive but be developed specifically for each site with a focus on key uncertainties. It is unlikely that a one-size-fits-all approach will be possible across all tidal projects.

To ensure the success of site-specific monitoring, early engagement between project engineers and those responsible for environmental monitoring is of paramount importance. The path forward most likely to succeed is the development of an integrated monitoring system that is tied to the turbine, with power and data transmission capabilities integrated into the turbine control system. Systems that can be broadly deployed with minimal tailoring at each site are the most likely to win support and allow progress. Early engagement with regulators to understand the potential post-consent monitoring needs and adaptive management options is also of upmost importance.

3.4.11.3
PRIORITIES FOR THE DEVELOPMENT OF METHODOLOGIES AND TOOLS

Marine mammals are generally challenging to detect and track; conditions in tidal-stream environments make this activity even more difficult. Limited success has occurred using cameras and strain gauges. Visual observations are hampered by turbid conditions and darkness. The development of integrated multi-sensor monitoring packages (e.g., Polagye et al. 2014; Williamson et al. 2015; Bromley et al. in press), incorporating passive and active acoustics, should be encouraged; however, consideration must be given to the optimal spacing of the different monitoring modalities. For example, a passive acoustic array capable of detecting and tracking echolocating cetaceans around a turbine would benefit from elements being equally spaced around the MRE device with spacing in the low tens of meters, whereas the optimal spacing of a multibeam sonar device for detecting and tracking marine mammals will depend on the beam geometry and the dimensions of the turbine. High-resolution acoustic cameras tend to cover very short ranges, while multibeam sonars can generally only provide 2D resolution of movement. Work on multibeam sonars is under way at the University of St Andrews where a technique for 3D tracking using dual multibeam sonars is being developed (G. Hastie, personal communication).

There is also a need to rapidly develop analytical frameworks for the data that will be generated from these deployments. While algorithms for the detection of echolocating marine mammals using passive acoustic means are well developed for many species, a degree of automation could be added; in addition active acoustic automatic detection techniques require development. Current sonar algorithms are capable of detecting marine mammals but suffer from a high degree of false positives. The ability to localize and track subsequent detections in 3D requires development for both passive and active acoustics.

While integrated monitoring systems, strategically placed near MRE devices, are likely to increase our understanding of avoidance and evasion behaviors, their resolution is likely to preclude assessment of actual collisions. It is essential that we determine whether collisions are actually taking place, through the development of reliable collision sensors. Animal-borne telemetry devices have the potential to provide information about the behavior of marine mammals around MRE devices, although the spatial and temporal resolution of most tags generally limit their usefulness for understanding fine-scale behavior and evasion abilities. It has been proposed that animals that do not reliably vocalize (e.g., seals) could be tagged with acoustic "pingers" if a passive acoustic array is being implemented to detect and track echolocating cetaceans (such as those used to track fish; e.g., Cooke et al. 2011), although it is important that the ping frequency lie outside the hearing range of the local marine mammals, to avoid changes in behavior or injury. This would allow a relatively large number of animals to be tagged and tracked using a passive acoustic array. To take advantage of the existing passive acoustic monitoring (PAM) array rather than using additional receivers, development of appropriate detection modules in PAM software would be required. Pinger tags could also be developed to be attached to the flippers of seals and therefore not fall off during the annual moult, thereby allowing animals to be tracked for longer periods of time.

Feasibility studies and roadmaps for mitigation are needed, in the event that mitigation is required. If collisions are shown to have the potential to pose a significant problem at the commercial array scale, automated detection and deterrence systems should be developed and tested. A review of deterrence systems that investigates the use of different sounds and frequencies to warn marine mammals of the presence of tidal MRE devices has been prepared for use in Scotland (Marine Scotland 2013).

3.5 FISH

Like marine mammals, many species of fish are considered to be potentially at risk around tidal turbines, based on their propensity to reef around structures in the water column, their importance commercially or recreationally, or an elevated regulatory status based on already depleted populations.

3.5.1 SUMMARY OF KNOWLEDGE THROUGH 2012

The case study on interaction of marine animals with turbine blades reported in 2013 (Copping et al. 2013) included summaries of four projects on interactions of fish with tidal turbine blades. Acoustic cameras were used to summarize movements (evasion and avoidance) at the ORPC turbine generator unit (TGU) but could not be used to determine whether individual fish were struck by the blades of the turbine. Only indirect evidence from the other studies could be used to determine the fate of fish (expression of avoidance or evasion) around MRE devices; e.g., high survival rates (99%) of eight species after entrainment through a Hydro Green Energy turbine in the tailrace of a hydroelectric dam (Normandeau and Associates 2009); 100 hours of daytime video footage revealed some avoidance of the area of the OpenHydro turbine during high flows but no direct interactions of fish with the turbine blades; and acoustic cameras at the Verdant tidal turbine deployment in New York revealed that fish were not present while turbines were operating, so direct interaction observations were not reported. Video laboratory observations were also somewhat inconclusive because of entrained bubbles and direct interactions were not observed. Laboratory studies revealed that survival of four different species (rainbow trout, juvenile largemouth bass, juvenile Atlantic salmon, and adult American shad) interacting with three different turbine designs (Lucid spherical, Welka UPG axial flow, and EnCurrent) at current speeds between 1.5 and 3 m/s was greater than 95%.

Collision risk was related to site-specific conditions using two different models. A geometric-area model revealed that risk varied by location and waterbody, and was dependent on placement within the channel and water column, as well as turbine operation (Schweizer et al. 2011). A three-dimensional predator-prey encounter model of a theoretical array of 100 turbines was used to evaluate risk to herring (Wilson et al. 2007). The model was sensitive to blade velocity and the animal's swimming speed and it was used to estimate that 2% of Scotland's herring population would encounter a turbine annually. However, model assumptions were somewhat unrealistic; e.g., even distribution and no expression of evasion, and the model requires validation. Another computational model revealed that the probability of blade contact for a 1.5 cm fish traveling through a 1 m rotor was 5% and for a 10 m rotor, the chances of contact would be 0.5%. The probability of contact increased with increasing size of fish passing through the rotor. Model results also indicated that the actual time a marine animal spent in the regions of the highest pressure changes associated with the turbine was a fraction of that required for pressure-related damage to occur (ABPmer 2010). These modeling exercises indicated the potential for severe interactions (Wilson et al. 2007; Schweizer et al. 2011). However, both assumed no evasion; direct observations in the field are needed to validate these models, making their predictive power limited.

The significant gaps identified in 2013 included the need for empirical data to be collected concerning fish interaction with blades of different designs, especially in waters with animal groups at risk or those that are commercially important. In particular, focused observations of the following are needed: open-bladed vs. ducted turbines; size of turbine vs. deployment depth; rotational speed; solidity of the rotor; foundation or anchor design; acoustic signature; and deterrents. In addition, laboratory studies should focus on appropriate species, particularly reefing/shoaling species that may be at higher risk. The need for more complex models of biophysics coupled with fish behavior around turbines, and multi-turbine array monitoring with assessments of cumulative and additive effects at geographically diverse locations, were identified. Finally, lessons learned included the need for learning by doing through adaptive management (Copping et al. 2013) and the need to develop new tools to estimate interactions and predict risk.

3.5.2 KNOWLEDGE GENERATED SINCE 2013

Realistic monitoring programs to investigate high-uncertainty risks of commercial-scale development have been considered previously in a workshop setting by experts (Copping et al. 2014). Technical limitations that need to be overcome to assess and monitor fish collision or risk of collision with MRE devices were identified and a spectrum of perceived risks was discussed—classifying risks from discountable to significant (must be mitigated). It was noted that four projects have been in the water for periods of months to years (6 years for SeaGen in Strangford Lough) with no observations of collision. However, observation systems were not in place for most of these installations. The need for research to develop transferable monitoring packages to observe collision was identified. It was generally agreed that modeling may still advance our understanding, but only when ground-truthing is possible. The use of probabilistic models to estimate biologically relevant levels of change was suggested with model parameters including energetics, behavior, and environmental covariates. The overall lessons learned from the workshop were that many interactions still cannot be monitored predictably; i.e., research challenges that remain include monitoring equipment installation, data acquisition, analysis, and interpretation. Tractable parameters, methods, and their limitations were identified. These parameters included monitoring the presence of fish around an MRE device using acoustic cameras and multibeam hydroacoustics, although it was recognized that this will not allow species recognition or detect collisions between fish and a device, both of which remain open research areas (Copping et al. 2014).

Since the 2014 workshop, newly available information includes models to explain encounter and collision risk of fish with MRE devices has been published in the scientific literature, including assessments of avoidance and evasion behaviors. These newer publications still focus on single devices although they are generally full-scale devices deployed in the natural environment (Bevelhimer et al. 2015; Broadhurst et al. 2014; Broadhurst and Orme 2014; Viehman et al. 2015; Viehman and Zydlewski 2015; Staines et al. 2015; Nemeth et al. 2014), as well as one scaled-down device (Hammar et al. 2013). Additional laboratory studies have been completed (Castro-Santos and Haro 2015) and published (Amaral et al. 2015). Advanced risk assessment (Hammar et al. 2015; Romero-Gomez and Richmond 2014) and probability of encounter models (Shen et al. 2015; Tomechik et al. 2015; Hammar et al. 2015) have also been published. Many of these studies are discussed further in following sections.

3.5.3 FLUME/LABORATORY STUDIES

Results from several fish-turbine interaction tests in laboratory settings suggest high survival rates (>95%). Researchers generally report evasive and avoidance behaviors because strikes are not typically observed, necessitating the assumption that any injury/mortality reported was associated with strike, though the studies caution that other sources of mortality such as net mesh entrainment, confinement sensitivity, and fish condition variability might have occurred (Amaral et al. 2014, 2015; Castro-Santos and Haro 2015). Castro-Santos and Haro (2015) used several monitoring tools in a semi-controlled laboratory/flume setting to examine fish behavioral responses and injury associated with upstream passage of adult American shad and downstream passage of juvenile Atlantic salmon around a vertical axis cross-flow turbine (EnCurrent Model ENC-005-F4) operated at up to 2.38 m/s. They observed a high survival rate for juvenile Atlantic salmon (98.3%), and that adult American shad were more willing to enter the flume in the absence of the turbine. Mortality for fish that passed through the flume was <5%. Statistical power of both negative results was low, so the authors cautioned interpretation and identified the need for a higher sample size to improve statistical power.

Amaral et al. (2015) combined a flume study and modeling exercise to determine the ability of fish to avoid rotor passage, strike injuries, and mortality. They modeled the probability of entrainment and survival given the ability to avoid turbines and compared estimates of passage survival among MRE turbine types. Injury and water velocity were positively related and the probability of injury increased with fish size; but there was no difference in survival rate between treatment and control groups for hybrid striped bass, rainbow trout, or white sturgeon with a Free Flow Power turbine with a 1.5 m diameter and seven blades, operating at 40 – 125 rpm in velocities of 1 – 3 m/s. Entrainment probability was low for rainbow trout and white sturgeon, indicating the ability to evade the device when they were released within 1.5 m upstream of the device at velocities of 1.1 – 2 m/s. However, hybrid striped bass were entrained at a higher rate (20 – 60%). The authors concluded that "most fish will be able to escape or evade turbine entrainment." The probability of survival for rainbow trout and white sturgeon was 1.00 while hybrid striped bass was 0.96 with the upper 95% confidence interval including 1.00. Behavioral responses under dark and light conditions did not differ, contrary to other reports that indicated visual cues are likely important for turbine avoidance (Viehman and Zydlewski 2015a; Hammar et al. 2015; Wilson et al. 2007). However, the authors concluded that nonvisual cues were important in promoting positive rheotaxis even though results were confounded in the dark at velocities greater than 1.5 m/s. Together these studies indicate some species and size-specific differences in behavior around MRE turbines.

Generally, these and other turbine laboratory experiments indicate that water velocity and fish length are important in determining whether fish are injured during entrainment, though no significant differences have been identified when comparing treatment and control groups in specific studies. Similar to conventional hydropower turbines the velocity vectors and hydrodynamic relationships between inflowing water and rotor blades are similar for conventional hydropower and axial-flow MRE turbines, and we would expect a similar relationship between fish length and strike probability and mortality to hold true for MRE turbines (EPRI 2011). However, conventional hydropower turbines have shear stress conditions, severe turbulence and gradients of pressure field that are considerably higher (EPRI 2011). Specifically, the relatively open configuration of MRE turbines allows fish to avoid/evade turbine passage and, if they are unable to evade entrainment, the slow blade rotation rate has been suggested to result in less damaging strikes and better fish survival than with conventional hydropower turbines (EPRI 2011). Romero-Gomez and Richmond (2014), using a particle-tracking model to estimate the probability of blade-strike injury as a function of length for a hypothetical, non-ducted, MRE turbine with blades 2.44 m high, found that greater fish lengths were associated with higher probabilities of blade strike and associated mortality (although they reported lower probabilities of strike with increasing water velocity). However, to date, a narrow range of fish lengths have been tested and higher survival at MRE turbines has been attributed to slower rotational speeds and strike velocities, perhaps leading to lower strike probabilities and mortality rates (Amaral et al. 2015).

3.5.4 FIELD STUDIES

Field studies includes investigations of evasion and avoidance near turbines, and baseline assessments.

3.5.4.1 EVASION AND AVOIDANCE

Field studies have been used to elucidate fish avoidance and evasion around several MRE devices (Bevelhimer et al. 2015; Viehman and Zydlewski 2015a; Hammar et al. 2013) and fish presence in the vicinity of turbines (Vieser 2014; Viehman et al. 2015; Broadhurst et al. 2014; Broadhurst and Orme 2014), yet fish strikes from field studies have yet to be observed (Viehman and Zydlewski 2015a; Broadhurst et al. 2014; Hammar et al. 2013; Nemeth 2014). Since the 2013 reporting of fish interactions with the test ORPC cross-flow device in Cobscook Bay (ORPC Maine LLC. 2014; Viehman 2012) further analysis revealed that there was a 51% probability of fish passing above or below the turbine blades while they were rotating and a 47% probability of the fish to enter the rotating turbine; the fate of the remaining fish was unknown (Viehman and Zydlewski 2015a). Fish species could not be separated using the acoustic camera, but their lengths ranged from 4 to 30 cm. Turbine evasion was 35% more probable while the turbine was rotating than when it was static, and evasion distance was shorter at night than during the day with an approximate evasion distance of 1.7 m for individuals and 2.5 m for schools.

Fish interaction with a full-scale axial-flow device (Verdant Gen5) in a tidal river system in New York was examined to quantify changes in fish position relative to the turbine, swimming direction, and velocity near the device (Bevelhimer et al. 2015). Using a bottom-mounted multibeam acoustic camera (DIDSON [Dual-Frequency Identification Sonar]), Bevelhimer et al. (2015) examined fish behavior while the turbine was operational, not rotating, and not installed (Figure 3.3). They observed fish <20 cm in length and found that there was no indication that behavior (swimming direction or proximity) was different during turbine operation than when it was not installed or not operating. However, they found that the fish's vertical location shifted deeper when the turbine was operating and that the numbers of fish in the area increased significantly once the turbine was removed, possibly indicating avoidance of the area while the turbine was deployed. Data are expected to be used in a strike model.

A vertical axis cross-flow turbine was studied during the daytime in a subtropical zone (Hammar et al. 2013). Authors observed no fish collisions with the rotor in place and no reduction in fish movement through the area while the turbine was in place. This was described as a deterrent effect and it was reported to increase with current speed. When the rotor was absent, fish movement through the area was not influenced by current speed. A similar response was observed by Viehman and Zydlewski (2015a). Avoidance occurred within 0.3 m of the turbine rotor for benthic reef fish and 1.7 m for larger predatory fish (Hammar et al. 2013). When the rotor was present the number of passages was reduced and the number of gap passages (not within the width of the rotor field) was significantly lower for the 37 genera observed. Assemblage-level effects were also observed. The overall genus level assemblage composition during control and treatment periods was dissimilar. Univariate tests for each genera found 5 out of 17 were significantly affected at all current speeds; at high current speeds (>0.6 m/s) the only genera affected were browsers, most of which had a compressed body shape. The power of the statistical tests for other genera was too low to reliably interpret. Evasion was observed for six genera and characterized as a startle response with a distinct turn and burst swim away; some species (wrasses) demonstrated more agile movements around blades and no fish strikes were observed. Only 19 fish (of 1757 total) were observed using burst swimming or another evasion tactics to avoid the rotor. The authors concluded that maximum swimming speed was of little importance for evasion of a single device. There was some indication of feeding guild differences in distance maintained from the rotor edge with browsers keeping a farther distance than invertebrate and fish feeders. Larger predators showed caution and were considered of low collision risk. The authors suggested that a single turbine may not be an issue. However, the presence of multiple genera with different life strategies could be affected by multiple turbines, potentially creating a barrier to reaching desirable habitats.

A similar video study was used to observe fish presence around a single ducted turbine (OpenHydro) deployed in the temperate waters of the UK (Broadhurst et al. 2014). Photographic stills were collected hourly over two 15-day periods (in two different years) during the deployment of the device. Shoals of fish appeared to use

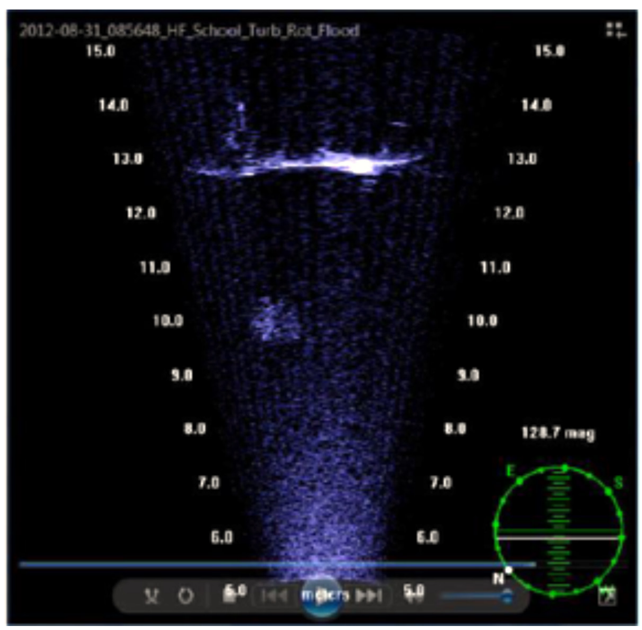


Figure 3.3. Plan view of the DIDSON acoustic camera field with turbine at the top of the figure and a passing school of fish in the middle. River flow was right to left. (From Bevelhimer et al. 2015)

the device for temporary protection or feeding and the single identified species, pollack, generally appeared in groups. Mean fish abundance was negatively correlated with water velocity. Patterns differed between years and there was no apparent threshold velocity that determined changes in fish abundance. The authors did not observe any collision or strike events.

Continuing with video observation studies, two river in-stream devices were installed and monitored on the Kvichak River in Alaska, USA (Nemeth 2014). The first device was the RivGen deployed by ORPC and the second device was the CycloTurbine deployed by Boschma Research Incorporated. Fish were monitored using video cameras and lights mounted directly on the devices. Ten-minute blocks from each hour of footage were subsampled for review. Fish were observed traveling upstream, downstream, and milling near the device. No fish were detected going through the RivGen unit and one lamprey was observed moving downstream through part of the CycloTurbine. Close examination of the lamprey was not possible because lights were not installed at the time. Most fish monitored were salmonids and were less abundant at the device than they were along the edges of the river. The effectiveness of video cameras and lights was shown to make detection of fish possible out to 10 to 15 ft during daylight and at night with lights on.

Swimming behavior data were gathered from a field study to characterize natural fish movements in a population viability model (Hammar et al. 2015). The researchers found that the presence of fish was negatively related to current speed; most species were very rarely present when currents were stronger than 1 m/s, indicating low probability of co-occurrence of fish with a rotating turbine. Fish that stayed in the currents swam with the currents, therefore increasing their likelihood of entering a turbine. As current speed increased, the probability of swimming at mid-water depths increased. Current effects on swimming were most pronounced between 0.7 to 0.8 m/s and the probability of fish entrainment increased with increasing current speed, especially those exceeding 0.7 m/s.

3.5.4.2
FISH PRESENCE IN A REGION: BASELINE

Broad ecological studies in MRE areas can provide an indication of the species that "inhabit or pass through the waterbody of an MRE device and can become unavoidably entrained in the water in front of a turbine," as has been identified for risk of collision above and by Amaral et al. (2015). By describing species assemblages present in these regions the possible negative effects can be narrowed down.

Attraction to devices has been shown to occur in predatory fish species (Broadhurst et al. 2014) with an associated increase in local biodiversity near the device (Broadhurst and Orme 2014; in the Fall of Warness tidal race of the Orkney Islands within the EMEC site with an OpenHydro device). The researchers concluded that the device site functioned as a localized artificial reef structure (especially for invertebrates). This study did not include a "before" installation component. A similar ecological study of previously uncharacterized finfish assemblages in tidally dynamic areas was examined in the United States. The study employed standard commercial otter trawl netting and nearshore seining to establish a baseline understanding of the fish assemblage prior to the installation of MRE devices in Cobscook Bay (Vieser 2014). Forty-six different fish species were documented along with temporal shifts in diversity and species presence. Both studies imply variable temporal ecological patterns, and the authors identified the need for longer-term studies but caution the stage of the industry makes longer-term studies difficult.

Fish presence and vertical distributions around a horizontal-axis cross-flow MRE device (ORPC TidGen®) were documented to understand the probability of fish being entrained at a certain depth of the water column that corresponds to the depth where the turbine was to be deployed (Viehman et al. 2015; Staines et al. 2015). Stationary down-looking hydroacoustics were used in a Before-After-Control-Impact (BACI) design in Cobscook Bay, Maine, USA (Figure 3.5). Generally, the proportion of fish tended to increase toward the sea floor, and the vertical distribution of fish only varied slightly over different seasons. The control site was comparable to the impact/turbine site (Viehman et al. 2015) before turbine installation, and vertical distributions were different before and after device installation, possibly as a response to the device itself (Staines et al. 2015), but sample size was limited to 3 months of operational deployment of the ORPC TidGen® device (Figure 3.4). This approach—seasonal, stationary down-looking hydroacoustics surveys—provided a repeatable protocol and useful data set to determine the potential effects of an operational MRE device on the vertical distribution of fishes. It allowed for robust comparisons between surveys conducted before and after device installation, and the concurrent use of a control site accounted for inter-annual variation.

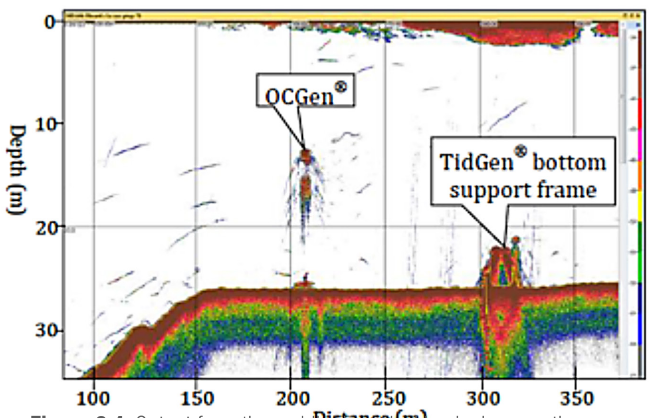


Figure 3.4. Output from the mobile down-looking hydroacoustic survey that involved transects in which the boat drifted with the current from 200 m upstream to 200 m downstream of the OCGEN® and the TIDGEN® bottom support frame during a flood tide. Fish aggregations are shown in the water column. (From Shen et al. 2015)

The timing and duration of occupancy, depth preferences, and patterns of striped bass in a tidal test site in Canada (FORCE) was studied using acoustic telemetry (Broome et al. 2015). Such data are relevant to informing our understanding of fish-device interaction because it is related to occurrence in a region and being present at the depth to be entrained into the water in front of a turbine (Amaral et al. 2015). Unfortunately, detection probabilities confounded an estimate of occupancy in the nearfield (<100 m) of a device but acoustic telemetry was effective for determining mid to farfield presence (>100 m). The data suggested that subadult striped bass were rarely detected in the proposed device location and therefore were at lower overall risk than adults. The authors emphasized the continued need for nearfield information about avoidance, evasion, and collision.

3.5.5 MODELS

Substantial progress has been made applying more complex models of fish collision with MRE devices (summarized in Table 3.3). While, to our knowledge, the SAMS model (Wilson et al. 2007) and the geometric-area model developed by Oak Ridge National Laboratory (Schweizer et al. 2011) have not been validated or further pursued, their basic ideas have been built upon.

3.5.5.1 PROBABILISTIC MODELS

Empirical data collected from various field studies have been used to develop simple probabilistic models to explain the possibility of fish encountering an MRE device (Tomichek et al. 2015; Shen et al. 2015). A 2D probabilistic model was used to understand the likelihood of an MRE (Verdant axial flow) device to strike Atlantic sturgeon in the East River, New York (Tomichek et al. 2015). The model was parameterized using seven probabilities to estimate that the probability of an Atlantic sturgeon being struck by a turbine blade is less than 0.1% (with no level of certainty indicated). This was the second iteration of this model and the authors noted that updating the model with monitoring data (additional acoustic telemetry data) better informed each probability and was useful to the industry and associated management agencies.

Shen et al. (2015) estimated the probability of fish encountering a rotor in Cobscook Bay based on their known distribution prior to turbine installation (Viehman et al. 2015). Three probabilities were used to determine that the total probability of fish being at the depth of the rotating elements of the ORPC TidGen® was 5.8% (95% CI: 4.3 - 7.3%). Combined with previous evasion data (Viehman and Zydlewski 2015a) only 50% of fish within 5 m of the turbine enter the device. Therefore, the probability of fish encountering a turbine blade would be less than 2.9%.

3.5.5.2 COMPUTATIONAL MODELS

Two different computational modeling approaches have been used to simulate blade strike at an axial-flow MRE device (Romero-Gomez and Richmond 2014). A computational fluid dynamics (CFD) model was used to determine the probability of impact by dividing the time a theoretical fish requires to pass the

Table 3.3. Comparison of model parameters used in recently developed models of MRE-fish encounter or collision, listed in order of mention in the text. The italicized text represents a common categorization to explain collision risk. Parameters associated with the categories estimated for each model are given.

Reference	Type of Model	Inhabit Area	Become Entrained in Water in Front of Turbine	Struck by Rotor	Receive Lethal Injury
Tomichek et al. 2015	2D Probability	Fish distribution/ occurrence	Fish distribution @ different water velocities; avoidance behavior (unknown)	Blade rotation; turbine rotor area; distribution of water velocity	Blade interaction[a]
Shen et al. 2015	1D Probability	Fish distribution (depth);	Avoidance behavior at two distances	Fish at depth of rotor within 3 m of rotor	
Romero-Gomez and Richmond 2014	3D			Time to pass plane; duration between blades[b]; particle simulation (based on mass, velocity and drag forces)[c]	Biological Performance Assessment (BioPA) Survival[d]
Hammar et al. 2015	Probability and population viability	Array passage	Turbine entry (dependent on: hazard zone, avoidance failure, co-occurrence)	Turbine injury (dependent on: hydraulic stress, collision, blade damage, evasion failure, blade incident)	
Amaral et al. 2015	Mark-recapture to estimate total passage survival		Probability of entrainment (multistate recapture); survival of entrainment (known fate);		Probability of injury (multistate); probability of descaling (multistate)

(a) Dependent on speed of fish (assumes maximum burst), length of fish, rotational speed of blade, angle of fish
(b) Not probabilities; the probability of strike is calculated using these two quantities.
(c) Used a fraction of collisions in the turbine-swept area
(d) Dependent on blade thickness, fish length, strike velocity; fish assumed to enter impact plane perpendicularly

blade plane by the duration of the gap between adjacent blades. A second approach, Lagrangian particle tracking, used a momentum balance equation and estimated fish as a neutrally buoyant sphere, to evaluate survival during a blade strike. These models reported on only those particles that would pass through the swept area of the turbine rotors and be capable of collision. Romero-Gomez and Richmond (2014) used the Biological Performance Assessment (BioPA) framework of Richmond et al. (2014) for conventional hydropower turbines to understand fish injury (as evaluated in the field and laboratory) as it relates to engineering design, based on the Lagrangian particle-based model. Their simulations suggested that interaction with a blade depended on 1) the release location of the neutrally buoyant (fish) sphere; 2) localized entrainment in a traveling eddy; and 3) the angular position of blades with respect to particle location as it crosses the blade. They then used experimental fish behavior data to determine that survival rates were relatively high (96.7 - 99.4%) with respect to experimental evidence of >90% (Amaral et al. 2015; Castro-Santos and Haro 2015). They concluded that the driving factor of the results was the low impact velocities (relative to conventional hydropower). The differences, with conventional hydropower and MRE designs explaining the lower impact velocities, included the fact that MRE designs do not compress fluid through the blades; the turbines do not constrain the approach path and have a lower blade rotation speed (Romero-Gomez and Richmond 2014). They postulated that shrouded turbines could have different results and warned that the model results should not be generalized to all MRE turbines because currently employed designs are highly varied.

3.5.5.3

POPULATION MODELS

Hammar et al. (2015) developed a probabilistic model to estimate population-level ecological risks. The model incorporated fish behavior, especially swimming behavior (avoidance) in strong tidal currents, into a population viability model to estimate the effects of turbine mortality on the population of fish in the region. Based on literature (Viehman and Zydlewski 2015a; Wilson et al. 2007) and their own observations Hammar et al. (2015) hypothesized two avoidance (more consistent with the definition of evasion earlier in this chapter) strategies: 1) reverse, i.e., change direction; and 2) diverge, i.e., swim toward the outer edge of the rotor. Option 1 would require the capacity to swim faster than the current speed. The modeled probability of failing to avoid a turbine varied over two orders of magnitude among fish taxa, strategy, current speed, light conditions, and turbine diameter. In most cases the probability of failing to avoid (in other words the probability of encountering) was above 0.10 in daylight, and 0.75 in low light. Failure increased with turbine diameter and current speed and decreased with light level. The model suggested failure to avoid (evade) would be high for any fish with low swimming capability relative to the current. The authors also indicated that the hazard zone of an axial-flow turbine is approximated to be two-thirds of the rotor-swept disk, and blade incident (i.e., strike) increased with fish length and decreased with current speed. Evasive maneuvers close to a blade were also considered; because large fish generally have lower agility but are less affected by the hydrodynamic forces around the blades, their chances of failing to evade were high. Blade damage was uncertain and suspected to vary by species and size. Based on the open design of MRE turbines the hydraulic stress was expected to have little impact on survival rate. The field case study of population status revealed a yearly loss of 650 specimens of 10,000. Model components can be refined for different case situations and informed by empirical data, especially concerning avoidance behavior.

Amaral et al. (2015) applied mark-recapture modeling techniques to assess the overall survival of individuals through four different pilot-scale MRE turbine designs using data collected in laboratory studies. Authors observed no fish collisions with the rotor in place and reduction of movement through the area while it was in place. Turbine entrainment was species dependent and current velocity highly affected the probability of entrainment. Total turbine passage survival probability ranged from 88 to 100%; adult American shad exposed to an EnCurrent turbine had the lowest probability of survival and rainbow trout had the highest. The probability of injury after entrainment was highest in hybrid striped bass, but injuries may not have been turbine related because hybrid striped bass that were not entrained had similar injury rates.

3.5.5.4

CONCEPTUAL RISK ASSESSMENT MODELS

Various forms of risk assessment have long been used to make decisions about uncertain environments when not enough is known about a system to establish a definitive estimate of the chance of injury or loss (Cox and Cox 2001). Busch et al. (2013) and Copping et al. (2015) used qualitative risk assessment approaches to understand risks of ocean energy development. Copping et al. (2015) developed a risk assessment framework for assessing risk in the data-poor conditions of MRE development. The framework involved ranking stressor-receptor interactions by the consequences of their occurrence to determine the potential effect of those interactions in an effort to assess anticipated cumulative impacts. While the process was limited by the lack of field data it was used to identify interactions that were likely to cause the most harm. For MRE-fish interactions the highest ranked were accident/disaster, leaching of toxic chemicals, noise, and presence of the dynamic device. These were all identified with highest potential consequences, albeit with high levels of uncertainty, for migratory and resident threatened and endangered species in the case study area of Puget Sound.

Busch et al. (2013) examined the ecological consequences of tidal energy development and climate change using a food web model and a risk framework. They used qualitative checklists to quantify the mortality of species in the Puget Sound that are listed under the Endangered Species Act (ESA). Using expert opinion of uncertainty and risk for six different environmental stressors associated with MRE deployment (static, dynamic, chemical, acoustic, electromagnetic, and energy removal), they developed qualitative risk tables. These tables were used in coordination with locally relevant literature about the effects of climate change on species in the marine environment (e.g., temperature, hydrology, sea level, ocean acidification, rare storm events) to explore the effects of species

Table 3.4. Methodologies and instruments applied to date (primarily since 2013) to understand fish collision with, strike by, and evasion and avoidance of MRE devices

Relation to Collision	Metric	Device	Method	Location	Reference
Inhabit Area	Presence in region	OpenHydro – 0.25 MW, 6 m diameter	Commercial fisheries benthic video	Isle of Eday, Orkney Isles – EMEC, UK	Broadhurst and Orme 2014
	Presence in region	ORPC TidGen®	Stationary down-looking hydroacoustics	Cobscook Bay, ME, USA	Viehman et al. 2015 Staines et al. 2015
	Presence in region	ORPC TidGen®	Otter trawls and beach seines	Cobscook Bay, ME, USA	Vieser 2014
	Presence in region	ORPC OCGen®	Down-looking hydroacoustics	Cobscook Bay, ME, USA	Shen et al. 2015
	Presence in region	Verdant Gen5 – axial flow	Acoustic telemetry and modeling	East River, NY, USA	Tomichek et al. 2015
	Presence at specified depth	FORCE, no turbine present	Acoustic telemetry	Minas Passage, Canada	Broome et al. 2015
Entrained in Water in Front of Device	Evasion, avoidance, attraction	ORPC RivGen®	Underwater cameras	Kvichak River, AK, USA	Nemeth 2014
	Evasion and attraction	OpenHydro – 0.25 MW, 6 m diameter	Video	Isle of Eday, Orkney Isles – EMEC, UK	Broadhurst et al. 2014
	Evasion and attraction	Verdant – Gen5 – axial flow	DIDSON	East River, NY, USA	Bevelhimer et al. 2015
	Evasion	Vertical Gorlov	Field – Stereovideo	Ponta Torres, Mozambique	Hammar et al. 2013
	Evasion, avoidance, attraction	ORPC – beta TidGen(R) – cross-flow	Acoustic camera (DIDSON)	Cobscook Bay, ME, USA	Viehman and Zydlewski 2015a
Struck by Rotor; Received Lethal Injury	Survival/injury, evasion, avoidance	EnCurrent Model ENC-005-F4	Acoustic telemetry, high-speed video, passive integrated transponder array	USGS Conte Anadromous Fish Research Center Flume, USA	Castro-Santos and Haro 2015
	Behavior and survival	Free Flow Power ducted axial flow	Video cameras, DIDSON for behavior	Alden Research Lab, USA	Amaral et al. 2014 and 2015
	Entrainment, survival	HydroGreen Energy	Balloon-tagged fish	USA - Mississippi River	Normandeau & Associates 2009

interaction with tidal power devices and climate change. They identified three major ecological effects associated with the combination of these changes: increasing hypoxia, tidal dampening, and temperature-related compromises to physiology affecting blade-strike harm. Total risk to multiple species was assessed along with trophic interactions. A mass balance food web model was used to assess blade-strike mortality for those species whose depth distribution was within the range of proposed tidal power projects in Puget Sound. They then modeled three scenarios of increasing numbers of turbines and differing temporal extents. The greatest risk observed was blade strike for ESA-listed species. However, when climate change and MRE development was assessed jointly, it became clear that climate change should be incorporated into assessments of MRE energy development, because failure to incorporate these and trophic-level responses could result in unrealistic expectations based on these qualitative analyses. The authors caution that the model parameters were based on expert opinion, not quantitative data and further experimentation needs to occur to inform our understanding of blade strike and the lethal consequences.

3.5.7 SYNOPSIS OF THE STATE OF THE SCIENCE

Knowledge gaps identified in 2013 that have since been addressed include assessment of fish responses to turbine rotation; the need for laboratory studies to focus on appropriate species; and the need for more complex models of biophysics with behavior and turbines at geographically diverse locations. We now have quantitative indirect evidence of the effects of MRE devices on fish behavior (avoidance and evasion; Amaral et al. 2015; Castro-Santos and Haro 2015; Viehman and Zydlewski 2015a), the subsequent effects on overall presence (Staines et al. 2015; Shen et al. 2015; Bevelhimer et al. 2015), and more specific assemblage-level responses (Broadhurst et al. 2014; Hammar et al. 2013). Some of these insights have been used to inform the development of computational and probabilistic models to better explain how strike or collision may be predicted (Hammar et al. 2015; Romero-Gomez and Richmond 2015) or even influence population sizes (Hammar et al. 2015; Wilson et al. 2007).

From these studies, there are common indications that fish may be affected by the presence of an MRE device, and most evidence is related to collision or strike being indirect. For example, to date the survival rate for fish passing through turbines is relatively high (>95%) and the probability of injury to fish is positively related to increasing water velocity (Amaral et al. 2015) and fish size (Amaral et al. 2015; Romero-Gomez and Richmond 2014). However, authors note the need for higher sample size data sets with more turbine designs and species groups to improve certainty and validate models. In addition, the numbers of fish in tidally dynamic regions seem to decrease with increasing water velocities when an MRE device is present (Bevelhimer et al. 2015; Broadhurst et al. 2014); fish were rarely present when currents were stronger than 1 m/s (Hammar et al. 2015). These data suggest a low probability of co-occurrence of fish with a rotating turbine (Hammar et al. 2015) and the probability of entering a turbine increasing with increasing current speed, especially at speeds exceeding 0.7 m/s. There is some indication that small fish evade turbine blades at distances less than 2 m from certain devices (Hammar et al. 2013; Viehman and Zydlewski 2015a) and that behavioral responses can be species-specific (Hammar et al. 2013; Amaral et al. 2015; Castro-Santos and Haro 2015). However, there is also some evidence that larger fish that stay in the water column at high flows will have a difficult time avoiding a turbine (Hammar et al. 2015). Models indicate that failure to avoid a turbine increases with turbine diameter (Hammar et al. 2015) and current speed (Amaral et al. 2015), and decreases with light level (Hammar et al. 2015; Viehman and Zydlewski 2015a). The probability of an encounter with MRE devices has been estimated between 1 and 10% depending on the region and species/assemblage studied (Wilson et al. 2007; Tomichek et al. 2015; Shen et al. 2015). Several studies imply variable temporal ecological patterns (Vieser et al. 2014; Broadhurst et al. 2014) that could influence whether species will be exposed to a device and inform how collision risk should be evaluated for a region.

The state of the science of fish-MRE interactions is currently in an early stage and progressing incrementally with the development of the MRE industry itself. New technologies progress through stages to eventually attain stability and ideally sustainability. Such progress includes changes in research, assessment, and monitoring approaches to document the environmental influences of the technology. As an external example, the development of environmental monitoring and regulations associated with steam-powered plants changed with the introduction of the Clean Water Act in the United States. In this case, the mature technology progressed to its highly informative present state of environmental effects with the combination of research and monitoring that involved technological advances of the environmental monitoring approaches themselves (Mayhew et al. 2000; Taft 2000). What is different between the steam-plant case and the MRE case is that the environmental impacts were realized once the steam-plant industry itself was at a relatively mature state and responded because of the promulgation of a legal mandate. In the case of MRE development, the industry and regulators have recognized the potential for effects and have taken a proactive approach to addressing them. However, this will take time and evolve through the growing pains of changing priorities and approaches as learning occurs along the way. The steam-powered plant industry, for example, experienced nearly 15 years of changes in environmental monitoring approaches to address the needs of the industry and regulatory bodies (Mayhew et al. 2000).

The MRE industry is nearing 10 years with only one turbine (MCT's) that has been deployed over multiple years and little concurrence on optimal MRE engineering designs. As the industry develops and matures the environmental monitoring approaches will also mature as priority parameters and techniques are realized.

Conventional hydropower is another good example of technology that has had a long-term research and monitoring history involving the evolution of the science of environmental monitoring to a point where fish passage has been improved. Today, empirical data have provided accurate estimates of fish passage, mortality, and injury associated with this technology (Coutant and Whitney 2000; Ploskey and Carlson 2004; Pavlov et al. 2002; Schilt 2007) as well as stochastic modeling that compares the movement of fish and neutrally buoyant surrogates around a hydroturbine (Deng et al. 2007). While some results from this research may provide insight into fish strike for MRE devices, significant inherent differences must be acknowledged. MRE turbines turn much slower, which is likely to decrease the probability of blade strike, and are unlikely to create hydrostatic pressure changes large enough to negatively affect nearby fish (EPRI 2011; Copping et al. 2013). While the comparability of animal-turbine interactions in analogous industries—e.g., conventional hydropower, oil and gas exploration, and nearshore pile driving—have been deemed somewhat peripheral to a true understanding of tidal turbine-fish interactions (Copping et al. 2013), lessons learned should not be ignored, rather they should be built upon.

3.5.8 CRITICAL UNCERTAINTIES

Progress has been made since 2013 to inform our understanding of the perceived risks of MRE-fish interactions. However, uncertainties remain. They range from the inability to monitor a specific event (e.g., strike) to developing the required confidence in the data that are collected (e.g., confidence intervals of those events that are measured). It is important to not only seek the former but identify the latter because poor-quality data can be misused with the ultimate result being failure to conserve the target of interest (Hermoso et al. 2015); e.g., fish populations around MRE deployments. While it is tempting to try to increase the amount of data acquired, additional collection of poor-quality data can lead to higher uncertainty and poor decision-making (Hermoso et al. 2015).

There has been significant research related to blade-strike experiments with hydropower technologies. It may be true that some of the findings from this research would be applicable to MRE-fish interactions in a broad sense, but major differences in the interactions themselves limit the application. This leads to one major critical uncertainty: what happens when a fish is struck by an MRE blade falls into the category of "unknown" uncertainty. While this seems to provide some indication that risk of strike is unlikely, without some record of these events we cannot draw this conclusion and are left assessing how fish avoid and evade devices. Researchers have demonstrated and postulated species-specific effects (Amaral et al. 2015; Castro-Santos and Haro 2015; Hammar et al. 2013; EPRI 2011) and have suggested that extrapolation beyond the taxa actually examined/tested is not appropriate (Hammar et al. 2013). Some researchers have indicated the importance of burst swimming for evasion (Wilson et al. 2007; Romero-Gomez and Richmond 2015), but others directly observed that very few fish used burst swimming as an evasion tactic to avoid the rotor and that maximum swimming speed is of little importance for evasion of a single rotor (Hammar et al. 2013). The most conducive conditions for observing volitional strike are under lit conditions, yet more fish are likely to be present under low light conditions (Viehman et al. 2015; Viehman and Zydlewski 2015a), making low light conditions more risky for fish because more of them are present and reaction distance is shorter (Viehman and Zydlewski 2015a; Hammar et al. 2013).

Computational models show promise for informing risk to populations associated with collision but are still riddled with uncertainty (Hammar et al. 2015), because of the lack of data for parameterizing them and the sparseness of data that are currently used. For example, the population viability model of Hammar et al. (2015) is limited by the following factors: the models should not be generalized, particularly at array scale because array passage will be site-specific; the probability of turbine entry must be species-specific (and we only have species-specific information for a handful of species); the turbine design must be considered because it has a large influence on potential mortality; natural fish behavior is needed to estimate collision risk but has not been included in most models; data are needed for model validation but none are available; and the differences between solitary fish vs shoaling fish behavioral responses must be considered (e.g., Viehman and Zydlewski 2015a, b).

The mechanism and frequency of injury from laboratory or field studies have uncertainty associated with them that transfers to the predictive nature of the models used to estimate effects on individuals or populations. For example, quantitatively characterizing the immediate environment around the turbines (inflow and outflow turbulence and high-resolution circulation modeling) themselves remains to be researched (Richmond et al. 2014). To do so, however, the turbine environment needs more robust quantification (as has been accumulated for conventional hydropower, *sensu* Richmond et al. 2014). Such quantification could be used to develop threshold criteria, e.g., minimum pressure for overall turbine design (Brown et al. 2012). Romero-Gomez and Richmond (2015) proposed that better data need to be collected on the trajectory of collision by accounting for the finite size of the sphere (i.e., fish) used in their model. These data had some concurrence with experimental data and are expected to be useful to regulators.

In lieu of modeling mechanisms of injury associated with fish-device interaction, avoidance behavior has proven useful here and for other industries. For example, Busch et al. (2013) noted that modeling avoidance helped to parameterize the number of blade strikes in models of wind turbines (Chamberlain et al. 2006) and that recording a lethal strike was required for full model parameterization. Similarly, accurate assessment of species vulnerability is dependent on having spatially explicit species density data, yet there is still uncertainty regarding the composition of animal assemblages in MRE environments, which can be informed by studies such as those by Vieser (2014) and Broadhurst et al. (2014). If we do not improve upon these uncertainties, the industry will need to continue its reliance on expert opinion and ecological theory (Busch et al. 2013). Indeed, there is some indication from conceptual models that ignoring trophic interactions could underestimate the risk of any individual action, and climate change effects could be so great that it would be difficult to discern the effects of tidal power development.

One of the largest uncertainties remaining at present is the scalability of results to date from single devices to arrays (Copping et al. 2013; Castro-Santos and Haro 2015; Amaral et al. 2015; Hammar et al. 2015). While most of the research cited above references the need to consider the effects at the array level, none of it provides clear certainty about how fish will respond to a single device or how to scale understanding to multiple devices or device arrays.

3.5.9 LESSONS LEARNED

Copping et al. (2013) identified the need to focus research and monitoring of risks on animals in relation to the following aspects of MRE turbines: differences between open-bladed and ducted devices; size of turbine vs. deployment depth; rotational speed; solidity; foundation or anchor design; acoustic signature; and deterrents. Since that time, direct laboratory comparisons of the open-bladed and ducted devices have not been conducted, but they have examined separately and a few scale-size devices have been compared via modeling (Amaral et al. 2015). Rotational speed has been assessed from a modeling perspective (Romero-Gomez and Richmond 2014), and, while deployment depth has not been pursued, studies have demonstrated that fish depth may be modified around open axial-flow and cross-flow MRE devices (Staines et al. 2015; Bevelhimer et al. 2015).

There is an increasing awareness of the importance of fish size, life stage, and trophic position when generalizing fish collision issues. It should be noted that larval and juvenile life stages have generally been ignored, but they have been suggested to be the most likely to interact with but not be harmed by a blade strike (Čada et al. 2007; EPRI 2011; Amaral et al. 2015) and the most likely to be entrained (Viehman and Zydlewski 2015a). However, this does not mean that every species, size, and life stage must be examined for interaction responses to MRE devices. Evidence from Hammar et al. (2015) suggests that fish feeding guilds influenced the observed responses. As such, separation of assemblages by feeding guild could inform responses to MRE devices. They particularly indicated that larger fishes, such as apex predators, while most able to avoid devices from a distance, may also be most vulnerable to collision risk because rotor detection and avoidance is difficult under conditions of low visibility (Hammar et al. 2015).

Field studies remain the most challenging due to the difficulty of working in dynamic tidal regions (Shields et al. 2011). However, researchers have collected data under these conditions and identified new opportunities for research in environmental monitoring techniques; e.g., the need for improved visualization of turbine structures to observe strike due to the inability of acoustic telemetry to examine mid-field avoidance and nearfield evasive behavior (Broome et al. 2015); the inability of acoustic imaging to examine visualization of strike (Viehman and Zydlewski 2015a); and limitations of working under low light conditions.

3.5.10 RECOMMENDATIONS

The amount of new information collected regarding fish-MRE device interactions is encouraging. However, because research is being conducted by separate independent researchers, better integration across research perspectives could help advance the state of knowledge for this field. At a minimum, terminology should be standardized. The most recent literature on MRE devices does not contain standard language regarding fish interaction with devices. For example, the distinction between evasion and avoidance is not distinguished by many even though the most common documented behavior is evasion (Table 3.1) and such documentation is needed for incorporating natural behavior in predictive models (Hammar et al. 2015; Romero-Gomez and Richmond 2015).

Standardization of language used around collision risk, collision, and behaviors associated with avoidance may benefit the industry and advancement of the science collectively, for example, to enable transferability of metrics across projects, methods, and studies (e.g., laboratory, field, and models). Similarly, standardizing a spatial scale for measuring responses, i.e., based on animal size or device size, could enhance the same transferability. Response distances have also been contextualized as "near" and "far" field, but should likely be considered relative to the size of the animal in question; particularly because more stereotypical behavioral responses (e.g., to predator risk) can be evaluated based on animal lengths (Weihs and Webb 1984). In addition, there may be ways to provide empirical evidence of a threat using the distance of the response (flight initiation distance, Lima et al. 2015). Because both evasion and avoidance will be dependent on sensory systems, and sensory modalities and sensitivities vary substantially across taxa (Lima et al. 2015; Martin 2011), life stage, and environmental conditions, all of these must be considered when establishing a common lexicon.

The rare probability of observing an occurrence of interaction or strike needs to be addressed. Strike events are expected to be rare, but on top of this, researchers are somewhat paralyzed by the amount of data that is collected to try to observe such events. There are available data sets that have only been subsampled (e.g., 24 hr of 48 hr collected, Viehman and Zydlewski 2015a; 5 still photos every hour for 15 days, Broadhurst et al. 2014) and they should be fully sampled to determine 1) whether there are missed events and 2) the probability of such events (to be factored into designing future research and monitoring programs).

The increasing awareness of the importance of fish size, life stage, and trophic position when generalizing fish collision issues may be addressed by considering group-level answers; e.g., feeding guild or habitat linkages as suggested by Hammar et al. (2015). Laboratory studies (Castro-Santos and Haro 2015; Amaral et al. 2015) can be used to target specific feeding guilds known to inhabit tidally dynamic regions targeted for development. Further analysis of assemblages of sites (e.g., Vieser 2014; Broadhurst and Orme 2014) could be used to inform the design and conduct of these laboratory tests and then analyses from both could be incorporated into models (e.g., Romero-Gomez and Richmond 2015; Hammar et al. 2015; Amaral et al. 2015). Such models have been used to suggest array design options; e.g., the need for turbine gaps of several meters between turbines in arrays (Hammar et al. 2015).

Options for reducing the probability of blade damage and incidence have been suggested by multiple researchers. Some identified solutions that included rating turbines based on rotational speeds, with lower speed being rated to represent lower risk (Hammar et al. 2015), which is supported by several different laboratory and modeling studies (Hammar et al. 2015; Romero-Gomez and Richmond 2015). Because visual detection of devices seems to be important for fishes (Hammar et al. 2013; Viehman and Zydlewski 2015a), increasing the detectability of a turbine by considering rotor coloration and addition of lights could reduce risk. Another option would be to use a stepwise system to slow down the rotor speed when animals approach, as suggested by Hammar et al. (2015). However, the ability to detect the animal's approach in time to slow the rotor could be difficult from a technical perspective.

Application of antipredator behavior to risk models and behavioral assessments has been explored and deserves further consideration. For example, estimation of the probability that an animal will encounter, or be co-located with, a turbine can be informed by predator-prey encounter models. That said, antipredator avoidance response cannot be stereotyped to all individual fishes' responses to a novel object because behavioral responses and underlying mechanisms controlling them vary across species. For example, habituation can make lethal contact more likely (Lima et al. 2015) and younger individuals may be more prone to contact/inability to evade due to inexperience (Blokpoel 1976). Generally, the diversity of fishes (20,000+ marine species alone) dictates high variation in antipredatory behavior avoidance reactions. Quantifying evasion is complicated by the response of individual animals because they may detect the object but not change their behavior (Lima et al. 2015).

Some consideration should be given to engineering turbines to minimize hydraulic conditions hazardous to fishes, as has been done for conventional hydropower turbines using BioPA (Richmond et al. 2014). This could help address the uncertainty that remains around the mechanism of injury and frequency of injury observed in laboratory and field studies by reducing the overall risk to the fish. Computational modeling with the incorporation of empirical data have shown some promise for informing risk assessments. It is recommended that additional models (e.g., individual agent-based) be parameterized as well.

The need for devices "in the water" to study under natural conditions continues to be emphasized. To do so, the industry should continue to consider decision-making using simulation-optimization and learn from experience by intelligent trial and error (Cox 2015). There is at least one successful example of an adaptive management approach in the MRE industry (Jansujwicz and Johnson 2015b), but it has not been universally embraced for various reasons. Cox (2015) suggests that in some situations models should be dispensed with and experiments should be run to 1) adaptively optimize the "value of information" from traditional decision analysis, 2) allow "low-regret" decision-making where the probability of selecting different actions is adjusted based on empirical performance and adaptive learning; or 3) apply "robust" decisions that will produce desirable consequences no matter how uncertain the models are. There is a rich theoretical base of robust optimization techniques (Chapter 7 of Cox 2015) that could be drawn from to inform how the industry interacts with environmental regulators.

In addition to better coordination of results, specific gaps need to be addressed by research studies, while others will best be filled by monitoring around deployed devices, or through development of specific technologies.

3.5.10.1 RESEARCH

Decreasing uncertainty will depend on being able to document what happens to a fish when it interacts with a device, and then being able to collect such data with a high level of certainty. Developing appropriate equipment for such purposes is important and has been recognized as a pressing issue as the industry moves toward the deployment of arrays (Copping et al. 2014). The fact remains that "direct observation of nearfield behavior of fish in the vicinity of operational tidal turbines" (as cited in ABPmer 2010) is still needed. As has been stated in the past (ABPmer 2010 and others), such studies could inform effective mitigation strategies. There is an obvious need for technical engineering research into new environmental monitoring technologies and packages that will inform or allow documentation of behaviors of interest, e.g., evasion or strike in the natural environment. Also needed is the development of new algorithms (that would be more accessible to the industry user) for processing data collected by various instruments that are not yet readily available, e.g., various multibeam sonar packages (Melvin and Cochrane 2015).

Several researchers have suggested integrated packages of instrumentation because environmental conditions (e.g., tidal stage, water velocity, light level, source noise) together determine the operation of the turbine and probability of strike and encounter. For example, photography could be used to evaluate ecological interactions, but must be accompanied by flow measurements (Broadhurst et al. 2014) because fish interactions with devices are dependent on flow and turbine responses to that flow. This would also address the need for comparisons of periodic tidal patterns (spring/neap) to understand the fluctuation of fish abundance (Broadhurst et al. 2014; Viehman and Zydlewski 2015b). An integrated package could also include acoustic telemetry for understanding behavior around a device (Broadhurst et al. 2014; Broome et al. 2015). Finally, the importance of replication across key variables (e.g., turbines and locations) would be important to informing the industry.

There is a need for more research into the frequency of sampling needed to really understand the effects of tidal turbines over an entire year. Short- and long-term periodicities exist in fish presence in tidal areas (tidal, diel, and lunar); such periodicities can be used to determine the optimal sampling frequency for monitoring device installations (Viehman and Zydlewski 2015b).

There is a continued need for laboratory studies of nearfield behavior of fish in the vicinity of rotating blades and documentation of collision damage. Tests of a wider range of fish lengths (Amaral et al. 2015) and species (or guilds; Hammar et al. 2015) are needed to more completely understand the potential impacts on fish populations and communities. Subsequently, these data can be used to better inform computational models. However, models need to be expanded to include multiple MRE turbine types (until a uniform design is reached); current model results cannot be generalized to all MRE turbines because they are highly varied. Current models also need better ability to calculate the trajectory of collision by accounting for the finite size of a sphere (i.e., fish in Romero-Gomez and Richmond et al. [2014]) by applying natural behavioral responses (as suggested by Hammar et al. [2014]).

Better basic understanding of fish responses to novel objects is still needed. Future advances will rely on systematic empirical studies of a range of behaviors and taxonomic diversity. For the MRE industry then, more research on sensory modalities and properties across taxa to determine the detectability of objects (Lima et al. 2015) is needed. For example, are fish responding to the changes in the hydrodynamic environment or the noise produced by the device? To answer such questions, even though some information has been gathered, more information about device source noise is still needed across a wider range of devices and settings (Bassett et al. 2011; ORPC Maine LLC. 2014) to better inform models and mechanisms for response and mitigation efforts. Along the lines of understanding individual or species/guild-level responses to novel objects, direct comparisons of animal responses to turbines relative to predatory threats may be useful in better assessing whether responses can be “stereotyped.” Hammar et al. (2015) suggested that fish behavioral syndromes (e.g., boldness and cautiousness) or feeding guilds influenced the observed responses. These types of responses to the novel MRE turbine should be pursued.

There is a need to better document and understand small-scale tidal features (eddies, boils, rips, etc.) that might influence fish distribution and behavior. The swimming and maneuvering capabilities of fish under conditions of extreme turbulence should be investigated through laboratory and field studies to further inform the debate about how able different species might be to avoid collision.

The MRE industry should consider following the Romero-Gomez and Richmond (2014) approach of applying a BioPA framework similar to the conventional hydropower approach (Richmond et al. 2014) of applying a probabilistic design method to bridge the gap between laboratory studies of fish injury and mortality to develop a suite of performance indicators for injury computed from a CFD model. This still assumes the ability to identify injury mechanisms, again relying on laboratory studies and development of models across various turbine designs.

3.5.10.2
MONITORING

Understanding critical uncertainties, e.g., strike of an individual fish by MRE device parts, while vital to overall mechanistic explanations of the effects and ultimate impacts of MRE devices, may or may not be the best metric to measure during regular monitoring of an MRE deployment because it continues to be an elusive metric to measure. Quantifying this metric will likely require further development of equipment and technology that can function in the environment of MRE devices to observe such events.

It seems that the more indirect measures of MRE-fish interactions (and even collision risk) can be informed by standard protocols used to quantify fish presence (Viehman et al. 2015) and redistribution in the water column (Staines et al. 2015; Shen et al. 2015) over various temporal and spatial dimensions that would be dictated by the environment (riverine, estuarine, ocean) and assemblage of animals present. Broadhurst and Orme (2014), for example, suggest the need for more robust studies, citing BACI experiments and impact modeling, particularly as the state of the industry matures since the current state makes study designs challenging because of changing development plans.

3.5.10.3 DEVELOPMENT (METHODS, TECHNOLOGY, ETC.)

Specific limitations to the direct measurements of animal interactions with tidal turbines include turbid conditions and high flow regions that have difficult conditions for the technologies that would be best for monitoring the interactions, e.g., optical cameras (Copping et al. 2014). In addition, optical cameras can be functional under non-turbid daylight conditions, but several researchers have indicated the importance of the increase in fish density/presence at night (Viehman and Zydlewski 2015a) along with a change in behavior under such conditions that may affect the level of risk to the animals (Hammar et al. 2015). While strobes could be used to alleviate such conditions they may interrupt behavior (Hammar et al. 2015). Such conditions can be conducive to acoustic imaging systems, but acoustic imaging systems have proven difficult for long-term deployments (unless they are cabled to a power source), and the acoustic return from the edge of a turbine blade does not allow distinction between the animal and the blade (Viehman and Zydlewski, unpublished). Stereo-imaging systems are being developed to address some of these issues for the MRE industry (Joslin et al. 2014).

Multiple tools with triggering mechanisms for different scale lengths to assess collision and avoidance are being pursued (Blondel and Williamson 2013; Jacques 2014) and have been proposed (Stein and Edson 2013). Test deployments for up to 2 weeks have been conducted with a remote-sensing sonar platform that incorporated measurements of hydrodynamic conditions as well as the presence of marine animals using hydroacoustics and multibeam imaging (Blondel and Williamson 2013). Technical work continuing from this includes optimizing sonar integration and refinement of data processing. A combined acoustics package was also deployed in the Northeast Pacific in the United States (Jacques 2014) for 1 month to document fish populations/densities as an indirect measure of overall effect at the population/group level. With any of these standard acoustic techniques, target identification must be validated with additional physical sampling. While such systems, strategically placed near MRE devices, are likely to inform our understanding of avoidance and evasive behaviors, resolution is likely to preclude assessment of strike or collision, particularly of fishes, unless they are large-bodied.

Additional opportunities, outside of the MRE community, should be considered; e.g., application of Sensor Fish technology (Deng et al. 2010; Deng et al. 2014) to answer questions about turbine mortality. Engineering of devices like Sensor Fish (to a cost-effective level where large numbers could be produced) could result in better informed laboratory and field studies to move our understanding of fish-turbine interactions forward.

Recognizing that MRE development is occurring in a dynamic environment that is much broader than an individual fish being struck by a turbine is important, especially in light of the need for zero-carbon emission power resources. Therefore, an ecosystem approach must not be forgotten and clear goals for the future of MRE should be jointly established among all stakeholders. Concerns of stakeholders and regulators must continue to be addressed and the best path forward is continued engagement among stakeholders (industry, regulators, scientists, and community) about these issues (Johnson et al. 2015; Jansujwicz and Johnson 2015a), particularly as new information is accumulated and synthesized. As projects are deployed and knowledge is gained, data sharing and collaboration continue to be vital to industry advancement. Marketing the presence of the *Tethys* Knowledge Base to stakeholders will help, and the importance of synthesis across projects and regular networking of participating researchers and other stakeholders must be sustained.

3.6
SEABIRDS

Diving seabirds depend on the marine environment for foraging and may be at risk from MRE development.

3.6.1
MONITORING OF SEABIRDS INTERACTING WITH MRE DEVICES

Regulators and stakeholders are concerned that MRE devices may pose a risk to seabirds through collision mortality, disturbance and displacement, and habitat loss, if large numbers of devices are installed. Due to the infancy of the MRE industry and a lack of devices in the water, studies have often focused on the potential vulnerability or sensitivity of species, rather than empirically assessing effects or monitoring seabirds interacting with MRE devices. Most research and empirical studies to date on seabirds and MRE devices have focused on habitat use and potential displacement of seabirds due to the presence and operation of MRE devices rather than the risk of seabird collision with MRE devices. This is in part due to the technical difficulties associated with studying birds under the water and also due to a lack of operating devices to study. Limited guidance is available regarding the monitoring of ornithological impacts associated with MRE devices and, where it is available, it is usually generic (Jackson and Whitfield 2011). A review of the potential effects studies and impacts of MRE devices on seabirds follows.

3.6.1.1
DESK-BASED STUDIES

Several studies assess the risk that MRE devices may pose to seabirds using sensitivity analyses and analysis of previously published data on the behavior, ecology, and distribution of species. Wilson et al. (2006) used information available in the scientific literature to assess the likely collision risk associated with MRE devices. They concluded that the species groups most at risk were divers, grebes, gannet, cormorants, seaducks, and auks, although the risk was only considered to be moderate for most of the species, or moderate/high for gannet. However, they noted that for most species there is limited understanding of foraging ecology for species outside of the breeding season or for juveniles; there are currently no empirical data available on collision impacts of seabirds with underwater MRE devices.

Langton et al. (2011) summarized how tidal energy developments could affect seabirds, based on experience with other forms of disturbance, and exploring the possible changes in behavior and habitat that have the potential to increase a seabird's rate of energy acquisition from foraging, or energy expenditure, due to displacement from feeding grounds. Summarizing data about seabird abundance and distribution from sources in Scotland, the authors estimated that the risk to seabird species was likely to differ with MRE technology design and species (Figure 3.5).

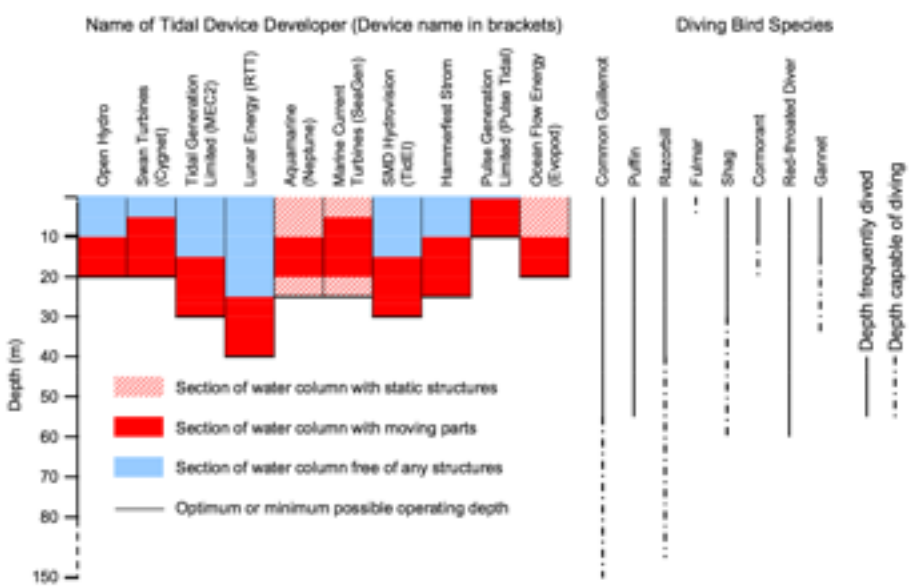


Figure 3.5. Estimate of the depths of the moving and static parts of a selection of tidal devices, when placed at optimal operating depths (minimum operating depth was used if optimum was unavailable) and the foraging depths of diving seabirds. (From Langton et al. 2011)

Furness et al. (2012) assessed the sensitivity of seabird species in the UK to the potential adverse effects of tidal turbines and WECs. Adapting the method of Garthe and Hüppop (2004), they assessed the conservation status of seabirds in the UK that may be present in areas of MRE development, as well as their vulnerability to tidal turbines and wave energy devices. Due to the fact that tidal turbines and WECs may affect birds differently, they considered these two classes of devices separately. Given the nature of wave energy devices, it was acknowledged that even the highest risk of collision due to structures would represent a relatively low risk for seabirds. Several elements of seabird behavior were included in the assessment for tidal turbines that relate to collision risk including mean and maximum diving depth and the use of tidal races for foraging. In terms of diving depth, the species that scored highly and were considered most at risk included European shag (*Phalacrocorax aristotelis*), great cormorant (*Phalacrocorax carbo*), common guillemot (*Uria aalg*e), razorbill (*Alca torda*), black guillemot (*Cepphus grille*), and Atlantic puffin (*Fratercula arctica*). This agrees with the assessment conducted by Langton et al. (2011), who reported that common guillemot, Atlantic puffin, razorbill, European shag, great cormorant, red-throated diver (*Gavia stellata*), and northern gannet (*Morus bassanus*) all dive to depths at which moving parts of tidal turbines can be expected to operate. In terms of the use of tidal races for foraging, European shag, great cormorant, great black-backed gull (*Larus marinus*), black-legged kittiwake (*Rissa tridactyla*), Arctic tern (*Sterna paradisaea*), as well as the auks (common guillemot, razorbill, black guillemot and little auk [*Alle alle*]) all scored highly. Furness et al. (2012) reported that black guillemot, razorbill, European shag, common guillemot, and great cormorant are all highly vulnerable to interactions with tidal turbines. This sensitivity analyses was extended by Wade (2015) to incorporate data uncertainty in an attempt to highlight areas and species where more targeted research is required.

3.6.1.2 VISUAL OBSERVATIONS

Visual observation can be used to monitor seabirds interacting with MRE devices. However, at this early stage of MRE development there are few opportunities to observe operational MRE devices in the water. As an alternative, studies have concentrated on the habitat use and behavior of seabirds in the highly energetic tidal channels where MRE devices are due to be installed. Such studies provide information about species that will potentially interact with the devices in the future.

MeyGen conducted boat-based and land-based observations to gather baseline data for its Inner Sound project in the Pentland Firth (MeyGen 2011). The boat surveys were conducted using modified European Seabird at Sea methods, and based on the methods developed for surveying offshore wind farm developments (Tasker et al. 1984; Camphuysen et al. 2004). Birds were recorded both on the sea surface and in flight; data were collected on the density of species recorded on the sea surface and on dive duration. The methods for the land-based observations were adapted from the methods used for land-based wind farm developments. The counts from the land-based observations were not suitable for the generation of bird density estimates, because the decrease in actual bird density with increasing distance from the shore was likely confounded by the decreasing detection rate with distance from the observer. European shag, black guillemot, and common eider (*Somateria mollissima*) were the species most frequently observed in the surveys, as well as northern gannet and northern fulmar (*Fulmarus glacialis*).

Wade (2015) also used land-based vantage-point surveys to investigate seabird behavior in the Inner Sound of the Pentland Firth. Wade (2015) found that different species of seabirds were present in the tidal channel throughout the year, and black guillemots and European shags were present all year. It was reported that not all species observed in the tidal channel used the site for foraging and only low numbers of birds were recorded diving in current velocities optimal for commercially generating energy from tidal devices. These findings suggest that highly energetic tidal channels may not be an attractive foraging habitat for most species of seabirds, implying that only a small number of bird species are likely to be at elevated risk of collision with devices. However, Wade (2015) found that most birds tended to dive into the oncoming current, which may suggest that diving species will be less able to detect devices if approaching facing away from them.

Rodger (2014) conducted similar land-based observations of another Scottish tidal channel, Bluemull Sound, a narrow tidal channel between the islands of Yell and Unst, Shetland. The objectives of the study were to investigate the relationship between the density of diving seabirds under conditions suitable for tidal generation (i.e., with the speed of the current), and over the tidal cycle. The investigator determined the foraging behaviors of the species present to determine whether there was likely to be an overlap with tidal turbines. Fieldwork was conducted by Rodger (2014) between January and March 2014; and 4118 individuals were recorded comprising 14 species. Of these, European shag and black guillemot were the most numerous. Results suggest that shag and black guillemot favored the fast, unidirectional current flow and the bird densities showed a positive correlation with current speed. Rodger (2014) reported that numbers of black guillemot show a clear peak during both ebb and flood currents and numbers were lowest during slack periods, but there was no clear relationship between abundance and the phase of the tidal cycle for European shag. An interesting behavior of black guillemots and European shags recorded by Rodger (2014) and termed the "tidal conveyor" was the tendency for the birds to be carried downstream on tidal currents, then fly a short distance upstream to repeat the process. Such behavior is clearly linked to the tidal cycle.

Waggitt et al. (2014) evaluated the use of shore-based surveys for estimating spatial overlap between deep-diving seabirds and tidal turbines, and simultaneously used boat-based surveys to identify bias in the shore-based method. They categorized the habitat within their field site at the Fall of Warness, Orkney, as either turbine or non-turbine microhabitats, according to mean spring tidal current speeds. They found that puffins, cormorants, and black guillemots were primarily in non-turbine microhabitats, while the numbers of sightings of larger auks were slightly higher in turbine microhabitats. Their research suggests that different species use different habitats based on current speeds.

3.6.1.3
TECHNOLOGY AND REMOTE OBSERVATIONS

The Hebridean Marine Energy Futures (HebMarine) project focused on wave energy rather than tidal energy, but the monitoring program for seabirds provides results that are pertinent to floating tidal turbines also. It has been suggested that MRE devices may provide roosting platforms for seabirds and may also act as FADs, further attracting birds (Inger et al. 2009). Seabirds are known to be attracted to and frequently recorded on large offshore structures, e.g., oil-gas production platforms. The HebMarine project assessed whether seabirds used the Pelamis wave energy device in these ways. Jackson (2014) used an autonomous camera deployed on the Pelamis Wave Power P2 machine at the EMEC wave test site at Billia Croo, Orkney, to monitor seabird use of the structure, and found that seabirds were clearly using the device. Eight species were recorded on the P2 machine by the camera system; the species that used the machine most was the Arctic tern. Other species regularly seen using the device were black guillemots and black-legged kittiwakes. Jackson (2014) considered the effect of the tide on seabird use and found that there was no particular pattern for Arctic terns or black guillemots, but kittiwakes were seen on the machine almost exclusively during ebb tide. In addition, black guillemots were regularly observed on the surface of the water next to the machine, particularly on the lee-side sheltered from wind-waves, and terns were seen feeding actively in surface disturbance caused by the device; these results may also be relevant for floating tidal devices. These seabird behaviors and responses to the Pelamis P2 machine are particularly relevant if floating tidal devices have moving turbines close to the surface of the water, rather than at lower depths in the water column.

Bird-borne technology (telemetry) can be used to effectively collect data about the potential risk from MRE devices, particularly time-depth recorders (TDRs) that record dive profiles and vertical use of the water column by diving birds. Langton et al. (2011) reviewed data on the species likely to overlap with tidal turbines in the water column. The black guillemot was not included in this analysis, despite being present at the MeyGen lease site and other areas of high tidal flow such as the Fall of Warness, Orkney, probably due to a lack of empirical data for this species. Previous data for black guillemots have been as bycatch in gill nets set at different depths (Piatt and Nettleship 1985). Masden et al. (2013) deployed TDRs on black guillemots breeding on Stroma, Scotland, and recorded individuals diving to an average depth of 32 m and a maximum depth of 43 m. The majority of dives were to the sea bottom for an average duration of 95 s and a maximum duration of 131 s. In addition they reported that 62% of the dives recorded in the study were in water deep enough to accommodate a turbine and that 37% of the diving time was spent between 8 and 26 m below the water surface, which encompasses depths where tidal rotors might be deployed. Black guillemots use depths within the water column at which tidal turbines are likely to operate and thus this species should be considered potentially vulnerable to collision (Masden et al. 2013)

Insight into potential collision risk can be gained by monitoring the area of interest for seabird use. The FLOWBEC platform (Williamson et al. 2015) has been used with a combination of sensors: an upward-facing multi-frequency echosounder synchronized with an upward-facing multibeam sonar; an acoustic Doppler velocimeter (ADV) to provide data on the local current flow; and a fluorometer to measure water turbidity. Williamson et al. (2015) deployed the platform at the EMEC site for five 2-week deployments to assess the interactions of birds (fish and marine mammals) with MRE devices. The platform has great potential for assessing collision risk for seabirds because autonomous detection algorithms have been developed for different species, and the range of depths and underwater behaviors can be identified, allowing for quantification of the amount of time different species spend in the water column near moving components. This is currently being developed for use by MeyGen in the Inner Sound of the Pentland Firth. A similar integrated instrumentation package is also being developed by Polagye et al. (2014); it would be able to monitor seabird interactions with MRE devices.

3.6.1.4 MODELING

Collision risk models have been used and form a central component of wind farm impact assessments, particularly in the UK (Masden and Cook 2016), and are now being adapted to assess underwater collisions (Band 2015). However, instead of adapting the model used for offshore wind turbines (Band 2012) to apply it to the estimation of collision for diving seabirds with tidal turbines, MeyGen (2011) developed an alternative method called the Exposure Time Population Model (ETPM) (Grant et al. 2014) to compensate for bird movement underwater and the birds' ability to perceive objects such as tidal turbines. The ETPM is designed to enable the identification of collision rates that, given a particular population size, would be considered likely or unlikely to occur, thereby providing evidence of whether impacts are significant. Using this model, the species sensitivity to tidal turbines in the Inner Sound of the Pentland Firth was considered not significant (MeyGen 2011).

The ERM and ETPM have been used to assess the likely risk of collision of seabirds with underwater tidal turbines (Band 2015), because they have been used to assess the interactions of other wildlife including marine mammals, as discussed in Section 3.4.5. These two models are similar in that they both use a physical model of the turbine and the body size and swimming activity of the seabird to estimate the potential collision rate. These models have been designed for marine wildlife as well as seabirds, and have therefore been discussed above in Section 3.5.3, Modeling and Data Inputs. Unlike large marine mammals, assessing collision rates for seabirds or other small animals with sizes comparable to or less than the chord width of a turbine blade, the Encounter Rate Model will likely overestimate the number of encounters due to the fact that it does not take into account the geometry of the blade and underestimate the likelihood that a small animal moving downstream may pass between the blades (Band 2015). For the collision risk model, the "double-cone"-modeled animal shape may be a suitable representation for most marine mammals and foot-propelled birds, but it is likely a poor model shape for diving seabirds, especially those that are wing-propelled (Band 2015).

Chimienti et al. (2014) have also modeled diving birds and tidal turbines; although their model does not specifically estimate collision, it provides insight into the behavior of diving seabirds when there is a tidal turbine in the water column. Their model represents a seabird performing a dive cycle in a vertical cross section of the water column, and includes simulations conducted to evaluate the efficiency of a predator foraging in an environment affected by tidal energy devices. Chimienti et al. (2014) highlight the fact that seabird movements, intervals between prey capture, and foraging efficiency are likely to depend on the distribution of prey and the size and distribution of underwater structures.

3.6.1.5
FUTURE PROJECTS AND PROPOSED MONITORING

Potential impacts on birds were assessed as to be negligible for the MeyGen project (MeyGen 2011), but MeyGen has committed to developing a bird monitoring program to improve understanding of potential impacts that could not be quantified sufficiently during the project environmental assessment. In terms of disturbance and displacement of birds at sea, MeyGen has provisionally proposed to conduct targeted boat- or land-based observations of all bird species to determine how habitat use or behavior may have changed over time; and to collect underwater noise measurements of the likely prototype tidal turbines. MeyGen has stated that understanding diving bird behavior around tidal turbines and the risk of collisions should be considered strategic research. It has proposed that its monitoring program will include the installation of one or more active monitoring systems on one or more tidal devices to better understand the nearfield responses of bird species to operating tidal devices, as well as other strategic research such as exploring the connectivity between the tidal site and local breeding colonies using geo-locating tags (MeyGen 2011).

3.6.2
LESSONS LEARNED

Insight into seabird collision with MRE devices is limited by the small number of devices that have been deployed and monitored. Waggitt et al. (2014) evaluated the use of shore-based surveys and demonstrated that in all cases, shore-based surveys are hampered by the observer's ability to detect foraging seabirds in fast tidal currents, which results in an underestimate of the number of seabirds that may use microhabitats around turbines. Wade (2015) highlighted the difficulties of observing and detecting seabirds out to 2 km from shore, particularly in turbulent tidal currents, and recommended that viewsheds for land-based surveys only extend out to 1.5 km.

Wade (2015) found that although seabirds use tidally energetic channels in the Inner Sound of the Pentland Firth, few seabirds forage in current velocities optimal for tidal turbine energy generation. Waggitt et al. (2014) reported that at the Fall of Warness, Orkney puffins, cormorants, and black guillemots were generally sighted in areas with mean current speeds less than 2 m/s. However, Rodger (2014) stated that black guillemots and European shags were recorded foraging in current speeds greater than 2 m/s in Bluemull Sound, Shetland, although the study did not specify the maximum current speeds in this area.

HebMarine used automated cameras to collect data from the Pelamis P2 device deployed at Billia Croo, Orkney (Jackson 2014) to show that some species of seabirds such as Arctic terns and black guillemots used the device. This finding may also have relevance to floating tidal turbines with structures above water and moving parts relatively close to the surface.

Lessons have also been learned from the offshore wind energy sector. Survey design protocols used for UK "Round 2" offshore wind farm seabird surveys were not able to detect changes in numbers of seabirds (Maclean et al. 2013) because seabird numbers fluctuate greatly at any given location over time. Maclean et al. (2013) suggest that by incorporating hydrodynamic variables into trend analysis, the power to detect change would increase; this may be even more important in tidal channels with high current flows. Although Maclean et al. (2013) were discussing displacement and changes in habitat use, such survey data (i.e., how many birds use the area) will be an important component of assessing the risk of diving birds colliding with tidal turbines. Statistical modeling methods used by the MRE industry are designed for detecting impact-related changes, but such methods may also be used to produce inputs for collision risk modeling (Mackenzie et al. 2013). Research undertaken by Masden (2015) incorporates variability and uncertainty into collision estimates. Masden (2015) highlights the sensitivity of collision estimated from the Band model to variability and uncertainty (Band 2015). A Monte Carlo simulation update is suggested to provide estimates of the magnitude of collision events and the likelihood of their occurrence, because the effect of variability and uncertainty is equally relevant in the underwater environment where little is known about the behavior and likely interactions of seabirds with MRE devices.

3.6.3 RECOMMENDATIONS

Many of the priorities for reducing the risk of seabird collisions with MRE devices that should be addressed by research, monitoring, technology, and monitoring tools are likely to overlap with those proposed for marine mammals and fish, including those listed below.

- Priorities for research
  - inclusion of variability and uncertainty in collision rate modeling.
  - improved understanding of the fine-scale spatial and temporal use of tidal habitat by diving seabirds, and links to oceanography through the development of suitable models.
  - development of methods to improve the understanding of the close-range behavior of seabirds around operating devices, particularly in terms of avoidance and evasion.
  - development of a method to detect (with confidence) any collisions of seabirds with turbines.
  - development of collision risk methods that incorporate the movements of seabirds around large turbine arrays rather than single turbines.
  - determination of population connectivity and methods to assign seabirds seen at MRE sites to breeding populations in order to assess which populations will be affected.
  - inclusion of the nonbreeding season impacts into population assessments.
  - improved understanding of the displacement of seabirds from operating MRE sites because it will influence the number of birds onsite to be at risk from collision with an MRE device.
- Priorities for monitoring at future tidal energy sites
  - monitoring of close-range interactions of seabirds with deployed devices.
  - targeted observations (rather than generic monitoring) of seabird habitat use in relation to tidal/oceanographic features to improve our understanding of how seabirds use the high flow environments.
- Priorities for technology development
  - development of collision sensors to ensure that any collisions can be detected with confidence and that collisions can be classified to species groups, i.e., marine mammals, fish, seabirds, rather than marine debris or flotsam.
  - development of a method to obtain diving behavior data from seabirds at known locations that are relevant for MRE sites. For example, the combination of GPS and TDR tags suitable for diving seabirds (including small diving seabirds) to enable diving behavior data to be attributed to specific locations for which tidal and habitat data are available.

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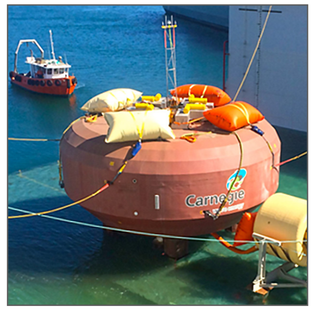

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Risk to Marine Animals from Underwater Sound Generated by Marine Renewable Energy Devices

The effects of acoustic output from tidal and wave devices on marine animals were previously addressed in the 2013 Annex IV report. The purpose of this chapter is to provide an update of new knowledge relating the effects of underwater sound from wave and tidal devices to marine animals.

4.1 GOALS AND OBJECTIVES

The goal of this chapter is to summarize the state of knowledge of the effects of acoustic output from tidal and wave devices on marine animals from marine energy projects worldwide. The chapter objectives are as follows:

- Provide a synopsis of material previously addressed in the 2013 Annex IV report.
- Summarize new or update previously reported findings from in situ studies and modeling efforts about sound generated from wave and/or tidal devices.
- Address existing gaps in data about the effects of underwater noise on marine organisms from wave and tidal devices.

4.2 APPROACH

To date, commercial-scale development has yet to occur; therefore, relevant data are limited to deployments at discrete locations consisting of small-scale devices and/or single devices. Assessing the effect of noise on marine organisms from wave and tidal device locations is accomplished by using a combination of approaches, including human observers and optical or acoustic measurements. Numerical modeling is also used as a predictive tool for evaluating environmental changes and potential biotic responses.

4.3 SOURCES OF INFORMATION

In addition to knowledge summarized in the 2013 Annex IV report (Copping et al. 2013), newer material was gathered from the scientific peer-reviewed literature, monitoring reports for MRE devices, and research studies, where available. In general, there have been few new studies or modeling efforts that further our understanding of the effects of noise from MRE devices on marine animals in the past three years.

4.4 SUMMARY OF 2013 ANNEX IV REPORT

Information about the effects of underwater noise from MRE devices on marine animals was presented in the 2013 Annex IV report (Copping et al. 2013). This section provides a summary of that case study.

Animals use sound in marine environments for communication, social interaction, orientation, predation, and evasion. The extent to which marine animals detect and emit sound varies by frequency and amplitude. The addition of anthropogenic noise sources from operational wave and tidal devices may induce behavioral changes and, in extreme cases of exposure, physical harm, especially for organisms perceived to be at particular risk of increased noise: marine mammals, fish, diving birds, possibly sea turtles, and some invertebrates (DOE 2009; Wilson et al. 2007). Potential effects of anthropogenic noise sources on marine organisms are dependent on individual species' responses, as well as characteristics of the noise source, including amplitude, frequency, and characteristics of how the sound propagates through seawater. A plausible range of physical impacts from high-intensity underwater sound includes temporary or permanent reduction in hearing ability, damage to non-auditory tissues, irregular gas bubble formation in the tissues of fish and marine mammals, and neurotrauma (Gotz et al. 2009; Halvorsen et al. 2012; Oestman et al. 2009). Noise of this intensity is not anticipated from the operation of wave and tidal devices (Polagye personal communication). Underwater noise may also result in behavioral changes such as avoidance of or attraction to the source and may also include masking—interference with communication, navigation, and detection of prey (Clark et al. 2009; Gotz et al. 2009).

Approaches for measuring underwater sound have been developed with considerable investments over the last century. However, sound characterization in areas of high tidal flow or substantial wave activity has been poorly studied. These high-energy environments, which coincide with potential locations for the siting of wave and tidal devices, are sources of considerable natural sound—waves, wind, sediment transport caused by shear stress, and pseudo-noise (non propagating sound from turbulence acting on

Table 4.1. Summary of attributes associated with the wave and tidal projects that collected field measurements on acoustic data associated with ambient and/or device conditions. This table has been adapted from Copping et al. (2013, 2014).

Project Location	Device Type	Developer, Project/ Device Name	Project Phase	Project Scope	Sound Levels and Pressure Spectral Densities	Organism Type	Results
Strangford Lough, Northern Ireland	Tidal; two 16 m open-bladed rotors, attached to a pile in the seabed in 26.2 m of water	MCT (Marine Current Turbines) SeaGen™	Ambient	Used hydrophones to measure ambient noise	Range of 115 to 125 dB re 1 µPa	NA	High frequencies (200 Hz – 70 kHz) attributed to sound of tidal flow.
			Construction	Measure noise levels of construction activities and marine mammal response to construction noise	• Driving pin-piles: 136 dB 1 µPa at 28 m; 110 dB 1 µPa at 2130 m • Drilling: 20-100 Hz. Equiv. to background noise at 464 m	Harbor porpoise	Temporary displacement of harbor porpoises during construction. Baseline abundances resumed following completion of construction.
			Construction	Calculate the perceived noise levels by marine animals during drilling	• Harbor seal: 59 dB_{ht} at 28 m and 30 dB_{ht} at 2130 m • Herring: 62 dB_{ht} at 28 m and 25 dB_{ht} at 2130 m	Harbor seals, harbor porpoise, herring, dab, trout	Perceived levels of sound from pin-pile driller were generally lower than ambient levels of sound in the narrows. Calculations of perceived noise suggest marine animals in Strangford Lough were unlikely to be disturbed at distances more than 115 m from drilling.
			Operation	Determine harbor seal behavior in area of operating device	Ambient plus device signature	Harbor seals	No significant displacement of seals or porpoises. Marine mammals swam freely in the Lough during operation. Noted evasion at channel center during turbine operation.
Cobscook Bay, Maine, USA	Tidal; a single, barge-mounted, cross-axis turbine generator unit in 26m of water	Ocean Renewable Power Company, Cobscook Bay Tidal Energy Project	Operation	Measure noise levels of the barge-mounted turbine	Less than 100 dB re $\mu Pa^2/Hz$ at 10m	NA	At 200 to 500 m from the turbine, sound was not detectable above ambient noise within the bay.
East River, New York, USA	Tidal; six three-bladed unducted turbines bottom-mounted in 10 m of water	Verdant Power, Roosevelt Island Tidal Energy Project	Operation	Measure noise levels around the array of tidal turbines	Up to 145 dB re 1µPa @ 1m from the array	14 fish species in the area	During the study, blades on one turbine were broken and another turbine was failing, resulting in more noise generation than would be expected. Conclude sound at damaged turbine array did not reach levels known to cause injury for 13 species of fish examined.
Puget Sound, Washington, USA	Wave; 1/7th-scale wave buoy	Columbia Power Technologies, SeaRay™	Ambient and Operation	Measure sound signature of the wave device and surrounding area	• Ambient: 116-132 dB re 1µPa in frequency of 20 Hz to 20 kHz when ships were nearby. • Device: 126 dB re 1µPa	NA	Ambient noise levels masked the wave device sound. Sound from the SeaRay was closely correlated to the wave period.

the hydrophone). Distinguishing these natural sounds from those produced by a particular MRE device is further complicated by noise from other anthropogenic activities such as shipping. Generally, sound from tidal devices and WECs is of low amplitude, fluctuating with tidal state as well as wave height and period, such that the amplitude may be higher a few hours a day (for tidal energy areas) or change with the wind speed, fetch, and distant storm activity (wave areas).

Challenges associated with determining noise effects include the ability to 1) adequately distinguish the sound of wave or tidal devices from background levels; 2) model noise data from single MRE devices to represent sound propagation from an array of devices over differing spatial scales, with field measurements to calibrate the models; and 3) quantify the direct and indirect effects of sound from MRE devices on animals of interest. Determining the effects of noise generated from MRE devices on marine animals is further complicated by noise from natural sources and other anthropogenic sources.

Field studies that have characterized underwater noise and/or measured the potential effects of noise from devices on marine animals were described by Copping et al. (2013) for one wave and three tidal projects. Details pertaining to those projects are presented in Table 4.1. Information collected at that time did not indicate that underwater noise levels from operational MRE devices were likely to cause harm to marine animals, although very few definitive studies are available. Noise from certain installation and maintenance operations may generate higher levels of noise, but these operations are well understood from other industries.

4.5 NEW INFORMATION ABOUT THE EFFECTS OF NOISE ON MARINE ANIMALS

The following section includes summaries from two systematic review of underwater noise associated with wave and tidal devices, six field studies, and two modeling studies relevant to measuring noise associated with wave and tidal devices have been conducted.

4.5.1 REVIEW OF UNDERWATER NOISE FROM WAVE AND TIDAL DEVICES AND POTENTIAL EFFECTS ON MARINE ORGANISMS

Two recent efforts to review and summarize the effects of noise generated from MRE devices have been undertaken by The Crown Estate (Section 4.5.1.1) and the European Commission (Section 4.5.1.2).

4.5.1.1 UNDERWATER NOISE FROM WAVE AND TIDAL DEVICES

Commissioned by the Crown Estate, the purpose of the efforts summarized by Robinson and Lepper (2013) was to review the current understanding of underwater noise generated by wave and tidal devices. The scope of this review included both publically available documents as well as data collected for commercial purposes, primarily by developers. The review largely focused on existing noise data and the integration of these data into making general impact assessments as opposed to species-specific impacts (Robinson and Lepper 2013).

Robinson and Lepper (2013) note there have been 29 studies related to noise of wave and tidal energy development activities, and of these, 17 have measured noise during construction and/or operational phases. Research activities reviewed by Robinson and Lepper (2013) are presented in Table 4.2. Despite the seemingly extensive number of studies, Robinson and Lepper (2013) conclude there are actually few datasets of the quality necessary to characterize noise radiation from MRE devices which presents serious challenges for making impact assessments.

Challenges associated with noise characterization and impact assessments stem from the variety of methods which have been used to measure noise and the differences in reported metrics which make comparisons across projects and monitoring efforts difficult. Furthermore, high-energy environments present challenges for accurately characterizing noise (Robinson and Lepper 2013).

Uncertainties and existing data gaps outlined by Robinson and Lepper (2013) include the following:

- Operational noise of wave and tidal devices under a variety of conditions and technology types.

Table 4.2. Summary of research activities associated with noise measurements at wave and tidal device sites. This table was adapted from Robinson and Lepper (2013).

Region	Country	Study Location	Organization/Project	Date	Research Activity	Device Type
North America	Canada	Bay of Fundy	Bay of Fundy Tidal Energy Converter (TEC)	2009, 2012	Ambient noise. OpenHydro EMEC data used to estimate noise	TEC
	United States	Cobscook Bay, Maine	Cobscook Bay Tidal Energy Project	2010	Radiated noise from demonstration project; turbine deployed from barge	TEC
		East River, New York	RITE TEC project, Verdant Power	2011	Operational noise; three turbines	TEC
		Puget Sound, Washington	SeaRay	2011, 2012	Operational noise from demonstration project	WEC
			Admiralty Inlet	2011, 2012	OpenHydro EMEC data used to estimate noise. Marine mammal and fish study	TEC
Scandinavia	Denmark	Hastholm	Wavestar WEC	2012	Background and operational noise	WEC
	Norway	Kvalsund	Akvaplan-niva AS	2009	Characterization of 300 kW Hammerfest Strom tidal turbine	TEC
	Sweden	Lysekil	Uppsala University	2011, 2012, 2013	Baseline noise, operational noise; Lykesil L12 and WESA projects	WEC
Southern Europe	Portugal	Pico Plant, Island of Pico	Wave Energy Center	2010	Operational noise for EIA (Environmental Impact Assessment)	WEC
		Peniche	AW-Energy SURGE	2010	Ambient noise	
British Isles	England	Cornwall	Wave Hub	2012	Long-term hydrophone deployment	
		Falmouth Bay	Exeter University	2012	Installation and operational noise	WEC
		Lynmouth	Marine Current Turbines	2005	Baseline and operational noise	TEC
	Ireland	SmartBay	IBM Research and the Marine Institute Ireland	2012	Ambient noise	
	Northern Ireland	Strangford Lough	Marine Current Turbines	2008	Baseline and operational noise	TEC
	Scotland	EMEC Wave Test Site	EMEC	2011	Ambient noise Operational noise; Pelamis Wave Power	WEC
			Aquamarine Power	2011	Installation and operational noise	WEC
		EMEC Tidal Test Site	Voith Hydro	2010	Acoustic characterization of Dynamic Positioning vessel	
			EMEC	2008, 2011, 2012	Ambient nois	
				2011	Noise surveys of cable installation with Dynamic Positioning vessel	TEC
				2013, 2013	Operational noise; Tidal Generation Ltd (ReDAPT)	TEC
			OpenHydro	2010	Operational noise with drifting ears	TEC
		EMEC Nursery Wave Test Site	EMEC	2011, 2012	Ambient noise	
		EMEC Nursery Tidal Test Site		2011, 2012	Ambient noise	
		Sound of Islay	Scottish Association of Marine Science	2009	Ambient noise	
		Lewis	Aquamarine Power	2012	Noise modeling and desktop assessment of potential impacts	WEC
	Wales	Ramsey Sound	Swansea University	2011, 2012	Ambient noise	

- The ability to detect device noise over background sources and determine how this may influence animal behavior.
- The behavioral response by marine organisms to noise generated by single devices as well as arrays is largely unknown.

Despite the inherent challenges associated with noise characterization in the wave and tidal energy industry, from their review on existing data collection efforts, Robinson and Lepper (2013) concluded the following:

- It is unlikely that operational noise of wave and tidal devices will cause injury to marine organisms.
- Construction noise of wave and tidal devices may exceed noise levels experienced during operation; however injury to marine organisms resulting from construction noise is unlikely.
- Behavioral effects, resulting from construction and operation noise on marine organisms are unlikely at long distances from the site.
- Assessments of behavior near devices require quality data on radiated noise at wave and tidal devices.
- It is unclear how the interaction of radiated noise and background noise may affect marine organisms, because measurements of radiated noise from an MRE devices are often very difficult to distinguish from ambient noise.

Robinson and Lepper (2013) developed a prioritized approach for characterizing noise that would aid in the regulatory approval for wave and tidal developments:

- Development of a strategic coordinated approach aimed at characterizing noise generated during installation and operational noise phases.
- Use 'type-testing' measurements collected during the design testing stage, to validate theoretical models and reduce continued monitoring efforts.
- Create a standard suite of methodologies for measuring noise levels and facilitate comparisons of datasets across projects, locations, and technology types.
- Develop and validate models to clarify noise radiation associated with various design components of devices.
- Develop new technologies to address challenges of measuring noise associated with wave and tidal devices.
- Optimize the monitoring efforts aimed at characterizing ambient noise at test sites and/or appropriate proxy sites.
- To promote industry-wide coordination, data sharing and collaborations should be encouraged by regulators.
- Data collection should include nearfield and farfield stations as well as measurements of particle velocity and seabed vibration.

4.5.1.2
ENVIRONMENTAL IMPACTS OF NOISE FROM MRE DEVICES

As a European Union Commission project, MaRVEN (Marine Renewable Energy, Vibration, Electromagnetic fields and Noise), investigated the environmental consequences of MRE by reviewing existing literature and information about a variety of stressors associated with MRE devices and implemented a field campaign to characterize noise from a variety of device types.

Thomsen et al. (2015) note that understanding of noise propagation associated with construction and operation of ocean energy devices has increased substantially since 2006. Noise generated during construction of wind farms, especially from impact pile driving, is of particular concern because these levels generally exceed regulatory thresholds established by some EU Member States. Operational noise of wind farms occurs within regulatory thresholds, making these noise sources less of a concern compared to those encountered during construction phases. Less is known about noise generated during construction and operation of tidal and wave devices. However, Thomsen et al. (2015) surmise that construction activities may produce sound levels similar to those of wind farm construction activities, when similar activities are implemented. The operation of wave and tidal devices is expected to result in sound levels comparable to medium-size vessels (Thomsen et al. 2015). However, few MRE installations are likely to drive full size piles into the ocean floor, as is carried out for offshore wind development; the resulting noise levels for MRE installation are likely to be less than those for offshore wind.

Despite increased understanding of noise propagation during construction and operation of some MRE devices, there are still many gaps in our understanding of the hearing abilities and sensitivity thresholds for many marine organisms. Little is understood about hearing characteristics of marine invertebrates; somewhat more is known about noise effects on some fish species (Thomsen et al. 2015).

Information derived from field campaigns and controlled experiments of noise effects suggests construction of wind farms elicits responses from marine organisms that vary with species and activity level. Operational effects of noise are less well understood, but modeling efforts suggest some fish and marine mammals are capable of detecting operational noise from wind farms several kilometers from the source (Thomsen et al. 2015).

Based on a review of existing information about noise impacts from MRE devices on marine organisms, Thomsen et al. (2015) note the following:

- Modeling of underwater sound provides a means for evaluating effects on marine organisms and should be implemented as part of environmental impact assessments for MRE devices.
- Research has helped to minimize gaps in data about noise impacts from wind farms, but little is known about how these impacts might relate to wave and tidal devices.
- There are significant data gaps in the knowledge of hearing thresholds and effects on marine organism health from MRE devices. Additional information is needed about hearing ranges for a diversity of taxa, and the potential and extent of masking of natural sounds by operating MRE devices for multiple species.
- There are significant gaps in the data about the physical impacts of hearing shifts (permanent and/or temporary) in marine organisms caused by construction noise, as well as uncertainties about the long-term effects of the displacement of organisms due to sound fields.

The MaRVEN project undertook field studies of environmental effects of noise from two different wave device sites (Lysekil, Sweden and Kishorn, Scotland) and at a single tidal device site (Isle of Wight, England).

Noise was measured as sound pressure and/or particle motion. At the Lysekil site, it was determined that particle motion at wave heights up to 2 m would be detectable to a fish at a distance of 23 m, while the sound pressure level was below the hearing threshold for fish. A single Albatern SQUID device was deployed at the Kishorn wave site, showing that nearby vessel traffic and acoustic deterrent devices (associated with nearby fish farms) were dominant sources of overall sound at a distance of 400 m. Analyses of sound levels, during high sea states indicated that the contribution of sound from the single wave device was negligible.

Operational noise measured at the Isle of Wight tidal turbine site was primarily attributed to gear sounds of the turbines and the frequency converter. Most of the energy generated from the turbines ranged from 1 to 2.5 kHz. Within these dominant sound bands, operational sound was 10-15 dB higher than ambient conditions at a distance of 282 m from the turbines. This pattern of elevated sound during operational states was observed at both lower (200–400 Hz) and higher (>4 kHz) frequencies with the difference in sound levels being approximately 5 dB.

Thomsen et al. (2015) suggest that at approximately 500 m from the device, sound levels generated by the operating turbines are expected to approach ambient levels.

Thomsen et al. (2015) highlight the following knowledge gaps for noise effects of MRE devices:

- Dose response
  - Cumulative, long-term effects of sound exposure.
  - Effects of operational sound on masking or natural sounds for by cetaceans and fish.
- Exposure assessments:
  - Determination of the relationship between disturbance and sound level, sound frequency, and exposure related to mitigation measures.
  - Development of methods for establishing science-based risk maps that address the probability of occurrence and intensity of consequences.
  - Benthic fauna effects of ground waves resulting from pile-driving activities.
  - New construction technologies for MRE development.
  - Operational sound levels for wave and tidal energy devices.
  - Operational sound levels of MRE devices in low frequencies, i.e., infrasound.

Research priorities for evaluating the effects of noise from MRE devices on marine life outlined by Thomsen et al. (2015) include the following:

- Dose response
  - Effects of pile driving on species of particular importance (e.g., threatened/endangered, commercial, and/or indicator species) and evaluations to determine if these effects affect populations.
  - Effects of pile-driving sound on baleen whales.
- Exposure assessment
  - Understanding the complexities of sound fields generated by sediment vibration resulting from construction of MRE devices.

4.5.2 FIELD STUDIES

We have highlighted several new studies on noise associated with MRE devices below. In addition to those highlighted, related research has been undertaken to characterize noise from a turbine in a riverine environment. Polagye and Murphy (2015) describe efforts to measure underwater noise associated with varying operating states of a turbine in an Alaskan river. Perhaps not surprisingly, sound levels were higher during all operating states of the turbine compared with ambient conditions, and turbine noise dissipated with distance from the device. At the Portaferry Tidal Test Centre, Northern Ireland, Schmitt et al. (2015) specified that noise associated with a tidal turbine was dependent on the particular mode of operations; normal operation, freewheeling, and braking — each demonstrated distinct noise signals.

In marine environments, to adequately contextualize device noise, research has focused on quantifying ambient noise conditions. Malinka et al. (2015) noted that baseline noise in the Grand Passage, Nova Scotia, Canada, was greatest during peak floods compared with slack conditions. Ambient noise levels were influenced by wind conditions in the 0–2 kHz band and they generally increased with current speed. The implications for these findings suggest ambient noise is influenced by site scale factors (i.e., locations of concentrated flow), as well as environmental conditions that operate at variable time scales (Malinka et al. 2015).

4.5.2.1 THE LYSEKIL RESEARCH SITE

Occupying approximately 0.4 km^2, in depths ranging from 24 - 26 m, the Lysekil Research Site is located 2 km off the west coast of Sweden. The site consists of soft-bottom habitats characterized by a mean wave height of approximately 1.5 m and a mean wave period of approximately 5 seconds. With two WECs installed at the site, Haikonen et al. (2013) evaluated the noise emitted from operating WECs and the potential impacts on marine animals that may result from the operation of the device (Figure 4.1). The study was initiated during spring 2011 when significant wave heights ranged from 0.1 to 3.5 m. Because of challenges associated with the recording devices, the results of the study were limited to significant wave heights <0.5 m, and a maximum acoustic signal of 141 dB re 1 µPa.

Noise generated from the WECs was detected over ambient noise levels across all frequencies (Figure 4.2; Haikonen et al. 2013). The primary noise generated from operating WECs was characterized as a series of two or more pulses that were of short duration and high amplitude; most frequencies were below 1 kHz and had a peak amplitude of 145 Hz. The average sound from the WEC at 145 Hz was 121 dB re 1µPa, and the peak sounds measured 126 dB re 1µPa.

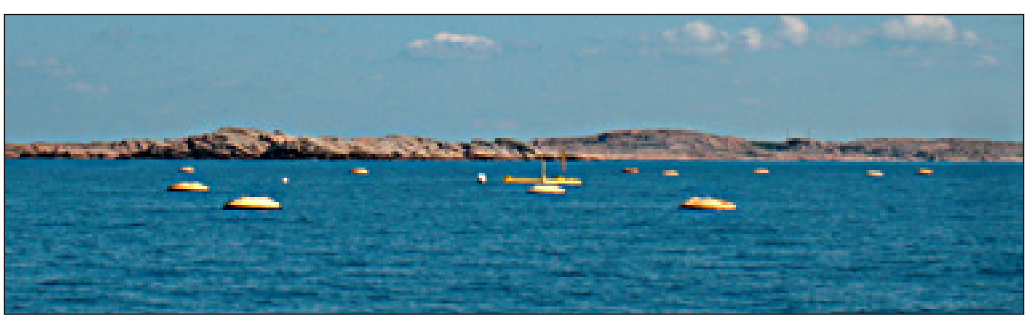

Figure 4.1. Wave energy converters (WECs) and environmental buoys deployed at the Lysekil Research Site. These WECs and buoys have been used for researching potential effects on benthic communities, reefing, and colonization. Underwater noise from a single WEC has also been investigated. (Figure from Haikonen 2014).

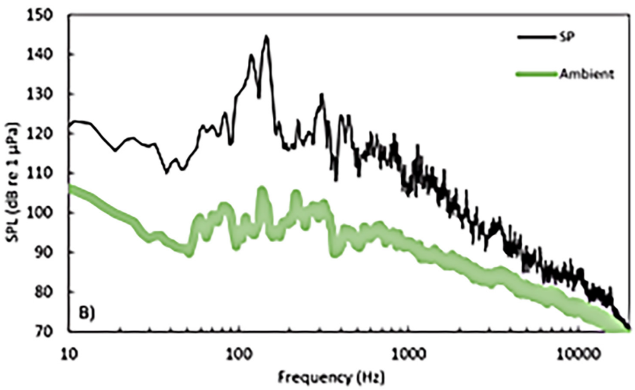

Figure 4.2. Single pulse (SP) noise generated from a WEC at the Lysekil Research Site compared with ambient noise spectral levels. WEC noise levels were measured 20 m from the device. (Figure from Haikonen 2014)

Haikonen et al. (2013) reported that at a distance of 20 m from the WEC, the maximum value for a single pulse was 133 dB re 1 µPa with an average of 129 dB re 1µPa, which suggests that many marine animals will be able to detect the noise from the operating WEC, but the noise was not sufficient to cause fish to change their behavior or be physically injured at the site. The WEC operating frequencies are below the hearing frequency for all but one marine mammal (harbor seal) considered at the test site. Noise within 20 m of the WEC could induce behavior modifications in this species. However, the authors calculate that at 150 m from the WEC, the noise will decrease by 32 dB and be at levels comparable to ambient conditions. Risk of injury from operational noise to marine mammals was thought to be unlikely. Haikonen et al. (2013) noted that it is unknown whether exposure to multiple pulses of noise generated by an operating WEC will result in a cumulative impact capable of inducing harm to a particular marine organism.

4.5.2.2
COBSCOOK BAY TIDAL ENERGY PROJECT

In 2012, the ORPC initiated construction activities at the Cobscook Bay Tidal Energy Project in Maine, USA. The TidGen® Power System consists of a TGU with four cross-flow turbines, installed approximately 9 m above the seabed, attached to a bottom-mounted frame. The frame is approximately 30 m long by 15 m wide by 4.5 m high. Acoustic monitoring of the device occurred during a previous test phase of the project with the turbine mounted on a barge; the results were summarized by Copping et al. (2013). The installation and operation of the single TGU in open water at the project site represented Phase I of the project, and included additional investigations to evaluate noise from the TidGen® Power System during generation and freewheeling (spinning without power generation) periods, and to assess how the noise levels might affect marine organisms near the site.

Because of the challenges associated with characterizing ambient and radiated noise in high-energy locations, a drifting noise measurement system (DNMS) was designed for acoustic data collection for the open water portion of the project. Data were collected over a two-day period in April 2013 that coincided with variable sea states, tidal phases, and turbine generator conditions. During generation and freewheeling states, noise was less than 120 dB re 1 $\mu Pa^2 Hz^{-1}$ (Figure 4.3). Turbine rotations per minute (rpm) during freewheeling were approximately 50% greater than rotations per minute during generation periods. Sound levels increased at frequencies of 105 Hz, 210 Hz, and 2.8 kHz and were scaled with turbine rotations per minute, which were typically louder when the turbine was in a freewheeling state than it was in a power generation state. Higher frequencies (5 kHz) were detected only during generation and scaled with turbine rotation. During periods of similar rotational speeds, the sound levels did not vary across distances spanning 20 to 300 m. ORPC Maine (2014) concluded that the combined ambient and operational noise associated with the turbine will be detected by some marine animals that occur near the project site. However, based on the noise levels detected during its investigation, behavioral responses and physical harm to marine organisms are unlikely.

4.5.2.3
WAVEROLLER

A prototype of the oscillating wave surge converter, the WaveRoller, was deployed in Peniche, Portugal. The device was deployed approximately 800 m from the shore in water depths ranging from 10-25 m. An experiment designed to characterize noise associated with the WaveRoller device as well as noise propagation was conducted during September 2014. Nearfield radiated noise was measured at 220 m and 350 m from the device. Propagated noise was measured at distances ranging from 300 m to 1200 m from the WaveRoller (Cruz et al. 2015).

From the data recorded nearest the device (220 m), Cruz et al. (2015) characterized sound ranging between 100 and 130 Hz and found that the SPL levels decreased

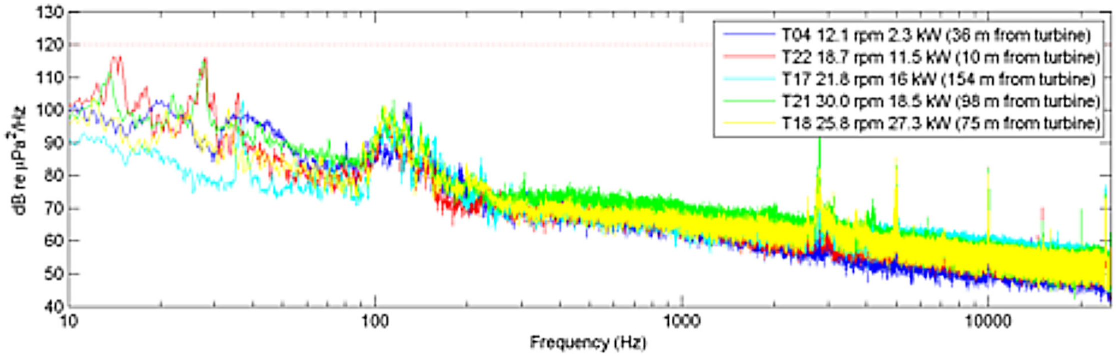

Figure 4.3. Power spectral density for the generating turbine at the Cobscook Bay Tidal Energy Project.

with power production, down to a frequency of 1 kHz. Results of the propagation experiment suggest that while noise is detectable at 1 km from the WaveRoller, the intensity of the noise dissipates within the first 300 m of the device and other noise sources become more dominant. Compared with noise generated from other marine activities (e.g., sonars, ships, pile driving), the noise emitted by the WaveRoller was small.

The WaveRoller produced sound below 125 Hz frequency, which is below the threshold for cetaceans classified in mid and high frequency hearing groups. However, Cruz et al. (2015) note that noise levels for the WaveRoller ranged between 115 and 130 dB re 1 µPa and speculated that such noise levels may elicit behavioral responses by certain cetaceans.

4.5.2.4 BILLIA CROO WAVE ENERGY TEST SITE

In May 2011 research on the operational noise of the Pelamis P2 system was undertaken at the Billia Croo Wave Energy Test Site. The purpose of these efforts was to develop methodologies aimed at characterizing operational noise as well as make comparisons between noise measurements at the site prior to installation of the WEC. Data at the site were collected with autonomous recording devices affixed to the seabed and boat-based drifting hydrophones. The maximum range of measurement from the Pelamis P2 system was 2.4 km. Lepper et al. (2012) note that comparing baseline to operational noise is challenging due to variation in ambient conditions. During operation, acoustic signals were generally lower than 2 kHz. Some acoustic signatures were attributed to nearby vessel traffic. There were distinct acoustic signals which were attributed to the Pelamis system; but there were also signals which could not be attributed to specific sources. Lepper et al. (2012) acknowledge the possibility that these sources may be related to Pelamis operation.

The placement of recording devices was such that acoustic signals associated with the Pelamis P2 system were evaluated at nearfield and farfield locations. Mean noise levels near Pelamis P2 were 133 to 137 dB re 1 µPa^{2}Hz and were 128 to 129 µPa^{2}Hz at positions farthest from Pelamis P2. These measured noise levels were similar to the modeled noise levels of the Pelamis system described by Richards et al. (2007). Noise in the 63 Hz band was noted in the recording devices closest to Pelamis, but was not detected from the devices located further away. Comparisons of operational noise at varying sea states indicates that higher sea states result in increased operational noise levels as well as increases in background levels.

This investigation provides data for noise associated with a specific device type, the Pelamis P2 system that had previously been unstudied. Lepper et al. (2012) suggest the high variability measured during baseline trials is likely driven by variable sea states in shallow water, the interactions of these environmental conditions with ambient noise are poorly understood. The noise range measured in association with Pelamis operations (100 Hz to 2 kHz) occur within the hearing range of most of the marine mammals thought to associate at the site, but refinements in methods used to collect these types of data will help to clarify potential impacts associated with wave and tidal devices in marine environments (Lepper et al. 2012).

4.5.2.5
WELLO PENGUIN COOLING SYSTEM NOISE STUDY

Underwater noise from the cooling system of the WEC, Wello Penguin was evaluated while the device was moored at the Island of Hoy in Orkney, Scotland. The cooling system is comprised of two fans and a single pump. A sonobuoy was used to collect underwater acoustic data 4 m below the sea surface in water depths approximately 10 m below chart datum near the moored Wello Penguin. Data recordings included a combination of stationary and mobile tows.

Ambient conditions, excluding interference of small vessels, ranged from 104 to 121 dB re 1 µPa with a mean of 112 dB rms re 1 µPa; values reported to be lower compared to nearby coastal areas (Beharie and Side 2012). Noise signatures from known sources at the site (e.g., ferry, small vessels, and mooring chains) were used to isolate noise from the Penguin system noise. Cooling fan noise yielded notable frequency peaks at 15 Hz, 45 Hz, 90 Hz, 140–150 Hz, and 250–300 Hz. Analyses of noise sources suggest sound pressure level of the Penguin cooling system were 140.5 dB rms re 1 µPa at 1 m with a transmission loss of 16.5 $\log_{10}$ (Beharie and Side 2012).

Beharie and Side (2012) note sound pressure levels may be variable when transmitted across the hull surface. It is anticipated that ambient background noise would be predominant within 10 m from the Penguin device in noisier wave energy environments.

4.5.2.6
WAVE ENERGY CONVERTER GENERATED SOUND

Noise from the Wavestar WEC was measured during operation, as well as stop and start modes, and combined with ambient sound data (Tougaard 2015). The operational WEC was found to produce a slight noise increase (1-2 dB) above ambient levels, which is unlikely to be detected by harbor seals, even at a short distance from the WEC. However, the stop and start sounds emanating from the hydraulic pumps exceeded ambient levels by 20-25 dB, which is likely to be audible to harbor seals. The frequency of the sounds from the Wavestar were believed to be lower than the hearing range of harbor porpoise which were also present in the area (Tougaard 2015).

4.5.3
MODELING STUDIES

4.5.3.1
HYDRODYNAMIC TIDAL TURBINE NOISE

Lloyd et al. (2014) used modeling techniques to predict hydrodynamic noise generated from a three-bladed tidal turbine. There were no field or laboratory-based data with which to validate the model, but they used predictions from an analytical model for validation. The predicted source level noise at 1 m from the turbine was determined to be 144 dB re 1 $\mu Pa^2 Hz^{-1}$, which is not anticipated to result in physical harm to fish species. The inflow turbulence noise peaked at <1 Hz, which is lower than the hearing thresholds for most marine animals. At higher frequencies, mechanical noise may be at levels that are detectable by marine animals. The predominant noise sources associated with inflow turbulence occurred near the tips of the turbine blades, resulting in noise radiation that is similar to a monopole structure. Lloyd et al. (2014) suggested that a reduction in tip speed would help to minimize noise levels, but acknowledge this may decrease the efficiency of the turbine. Alternatively, a reduction in the diameter of the turbine may help to minimize the noise output. Lloyd et al. (2014) also suggested that an array of multiple, smaller devices would minimize overall noise. Further evaluation of acoustic output from arrays is needed to determine potential effects such as masking of sound by marine mammals and other marine species.

4.5.3.2
WAVE ENERGY DEVICE SOUND PROPAGATION AND THE INTERACTION WITH BOTTOM SURFACES

Focusing on noise levels generated from a wave energy device, Ikpekha et al. (2014) modeled the interaction between noise propagation and seabed conditions within the context of hearing thresholds for harbor seals. Applying the model to shallow, soft-bottom habitats, the model parameters included water depth, sound source, and receiver location, as well as water density, sediment characteristics, and the speed of the sound in the water.

As sound frequencies from the WEC increased and substrate conditions were excluded from modeled scenarios, sound pressure levels were attenuated more rapidly with increasing distance from the source. However, when sediment conditions were applied to the model, the attenuation pattern became distorted by the interaction of sound with the seabed causing reverberation of sound and increased sound pressure levels. The scattering of sound pressure levels was amplified at higher frequencies. While not modeled, the authors suggest that hard-bottom substrates would result in higher sound pressure level values. The comparison of the modeled sound levels to an audiogram for harbor seals suggests that under select frequencies, seals would be able to detect the noise from a WEC at distances greater than 50 m. The addition of multiple wave energy devices could increase the overall sound pressure level and subsequently increase the distances over which marine mammals might be affected.

4.6 DISCUSSION AND IDENTIFICATION OF DATA GAPS

More information is needed to determine whether physical injury and behavioral changes caused by installation noise will be harmful. Research focused on elucidating noise radiation from MRE devices has applied a variety of techniques and approaches for quantifying sound, but as Robinson and Lepper (2013) point out, few datasets are of the quality necessary to adequately characterize noise for the purposes of impact assessments. Furthermore, many studies are based on a limited range of temporal and environmental conditions which limits the breadth of conclusions that can be derived from field investigations. While there is indication that some construction/installation activities may include harmful levels of sound that may temporarily displace marine animals, no studies have indicated that the level of operational noise from MRE devices is likely to be harmful to marine animals. Little work has been done to examine the potential effects of underwater sound on sea turtles and diving birds.

The state of knowledge has not increased greatly since the release of the 2013 Annex IV report because few studies have evaluated the effects noise from MRE devices on marine organisms. Field studies and modeling efforts that have occurred in the past few years are providing useful information toward understanding the effects of noise from MRE devices; however, there is still much we need to learn to facilitate development of the industry. The existing data gaps, outlined by Copping et al. 2013 still hold true as there have not been significant advances in the collective understanding of how noise impacts marine organisms:

- Field investigations should include 1) efforts to characterize ambient noise prior to deployment activities, and during calm conditions when the device is not operating, 2) accurate detection of sound generated from the device, and 3) observation of marine animals at the site using multiple detection methods appropriate for the organism of interest—observers, active acoustics, and aerial surveys.
- Laboratory studies will help to elucidate dose/response relationships pertaining to the response by organisms to various amplitudes and frequencies of sounds, in order to understand what levels and frequencies of sound may be problematic to marine animals likely to be in proximity to MRE devices. These studies should target fish and invertebrates at various life stages.
- Cumulative impacts of arrays need to be understood to aid in impact assessments for larger-scale development activities. Most field and modeling studies focused on wave and tidal devices involve characterization of a single device.
- If collisions are shown to have the potential to pose a significant problem around MRE devices, automated detection and deterrence systems might be used. A review of deterrence systems, including different frequencies to warn marine animals of the presence of tidal MRE devices, has been prepared for use in Scotland (Marine Scotland 2013).
- Understanding acoustic output conditions from a range of tidal and wave devices will help broaden the collective understanding of impacts and help developers make informed decisions about device specifications and potential noise impacts.

4.7 RECOMMENDATIONS

The state of the science on the effects of noise from MRE devices would be strengthened by strategic research focused on associated behavioral impacts on marine organisms. Research should be structured around noise and subsequent behavioral responses by marine organisms under a variety of environmental conditions, seasons, and operational states of MRE devices.

Research priorities include the following:

- Establish methods and techniques to characterize ambient noise in marine environments.
- Establish methods and techniques to accurately detect device-generated noise.
- Establish an international standard for measuring noise in association with MRE projects.
- Conduct laboratory studies aimed at establishing dose/response relationships by organisms with various amplitudes and frequencies of sounds, progressing to field experiments that document behavioral responses of animals around MRE devices.

Coordinated monitoring approaches, standardized methodologies, and new technologies for measuring noise in high-energy environments will contribute to the continued understanding of the interactions of MRE device-generated noise with marine organisms. Similar to research efforts, monitoring should focus on data collection under a variety of environmental conditions, seasons, and operational states of MRE devices.

Monitoring efforts at future wave and tidal energy sites should include the following:

- Site-based observations of marine animals to determine behavioral responses of organisms of interest, coupled with noise outputs from devices over operational cycles.
- Collection of device-generated noise during various operating states for the purposes of evaluating potential noise impacts on marine organisms of concern.

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5.0

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Changes in Physical Systems: Energy Removal and Changes in Flow

The effects of altering natural water flows and removing energy from physical systems in the ocean by the installation and operation of MRE devices were previously addressed in the 2013 Annex IV report (Copping et al. 2013). The purpose of this chapter is to summarize previous information about flow changes and energy removal caused by wave and tidal devices, including changes in sediment transport and water quality, and to update these findings with new knowledge.

5.1 GOAL AND OBJECTIVES

The goal of this chapter is summarize the state of knowledge of changes in the physical ocean systems caused by MRE projects worldwide. Objectives include the following:

- Identify recent wave and tidal projects with a monitoring program that addresses physical changes in the environment.
- Analyze details of recent laboratory experiments and numerical modeling simulations that help to inform the understanding of potential physical effects from MRE devices.
- Compare the cumulative understanding from recent studies with knowledge gaps identified in the previous Annex IV report to identify progress.
- Diagnose persisting knowledge gaps based on a review of available research.

5.2
APPROACH

This chapter focuses only on research and monitoring results that have become available since the 2013 Annex IV report (Copping et al. 2013).

Decades of reliable oceanographic measurements of tides, currents, waves, nutrient loading, and suspended sediment are available around the world. Yet these data collection efforts have rarely focused on high-energy sites where wave and tidal energy development is targeted.

There are few field studies of energy removal and changes in flow caused by MRE devices, but many numerical models have been developed and applied to the problem. Studies over recent years have begun characterization of these environments in anticipation of MRE device installations, producing data that may be input into models. A significant number of models have been created, but most modeling has focused on the determination of device spacing for power generation optimization. Fewer models have focused on environmental concerns like changes in water circulation, sediment transport, and water quality.

The push to develop MRE farms is driven by the need for new and diversified energy sources, as well as a means to move toward a renewable energy portfolio that helps to ameliorate climate change. At the same time, the shifting baseline of climate change in the oceans is certain to involve changes in prevailing wind and wave patterns nearshore and offshore, as well as potential changes in ocean currents, storm surges, and other natural phenomena (Harrison and Wallace 2005). As commercial MRE arrays are deployed and licensed for periods of decades, the effect of this shifting baseline will need to be accounted for in modeling simulations of MRE interactions with the environment, and for investigations into the future effects of the devices on the physical system.

The marine environment is naturally very complex and highly variable, particularly in high-energy environments where tidal and wave energy are best suited for power production (Shields et al. 2011). Examining the physical ocean environment to determine the potential effects of flow changes and energy removal is exceptionally challenging because the signal-to-noise ratio is very high, and the range of variability in proposed MRE deployment areas is not well known (Venugopal and Smith 2007). is very high, and the range of variability in proposed MRE deployment areas is not well known (Venugopal and Smith 2007).

5.3
SOURCES OF INFORMATION

In addition to knowledge summarized in the 2013 Annex IV report (Copping et al. 2013), newer material has been gathered from the scientific peer-reviewed literature, monitoring reports for MRE devices, conference presentations, and research studies, where available. In general, very few new studies or modeling efforts have furthered the understanding of the effects of changes in water flow and energy removal in the past three years.

5.4
SUMMARY OF KNOWLEDGE THROUGH 2012

The sustainability and health of the marine environment is dependent on physical systems that experience significant spatial and temporal changes due to natural variability, climate change, and anthropogenic pressures. In tidal basins, tidal currents drive circulation and flushing, helped along by freshwater input from rivers and streams, and heating at the air-sea interface. Complex bathymetry creates currents that facilitate the mixing and exchange of sediments, nutrients, dissolved gases, and contaminants. Along open coastlines, local and distant winds determine wave regimes, which respond to bathymetric patterns and atmospheric disturbances. It is within the highest-energy sites of this system that energy extraction is planned.

Introducing MRE devices is likely to affect the system by changing the flow around the devices, which can alter sediment distribution and transport, and by removing kinetic energy from the system in the form of electricity along the export cable (Polagye et al. 2011). Based on the scale of ocean basins and coastal areas, the changes due to a small number of MRE devices will not be measurable; however large commercial arrays might alter the system sufficiently such that change may be observed over time (DOE 2009). Researchers examine these interactions by collecting oceanographic data to quantify the background processes and potential changes caused by MRE devices, and by developing numerical models that simulate potential changes in the system. Field data also are used to validate numerical models; the models can be used to simulate changes in the ocean environment with the addition of large numbers of MRE devices without the risk and expense of engineering and deployment.

The previous Annex IV report (Copping et al. 2013) discussed two field programs that have collected data on the physical system pre- and post-installation of MRE devices: the MCT SeaGen turbine in Strangford Lough, Northern Ireland, and the Verdant Power turbines in the East River, in New York in the United States. Despite using the most sensitive instruments commercially available, both projects were unable to measure physical changes caused by the small number of MRE devices over the variability of tidal flows within the system.

Eleven modeling studies for both wave and tidal devices from Europe and North America were carried out previous to 2013 (Copping et al. 2013). These modeling efforts investigated topics such as the reduction of wave height, impact of climate change, effect on beach processes, abundance of macrofauna, sediment deposition, flushing of contaminants, changes in ocean circulation, energy available for extraction, and more. Based on the studies, it is apparent that numerical models present an important method for simulating the potential effects of large-scale buildout of MRE farms in coastal and estuarine waters. In general, WECs (wave energy converters) are more difficult to model than tidal turbines because wave energy is less predictable and variable over time and there are many more fundamentally different designs of WECs. Tidal energy devices and their environment are easier to model due to the predictability of the tides, extensive hydrodynamics modeling expertise in the oceanographic community, and similarities between tidal turbines and other energy generation gear, including wind turbines and conventional hydro turbines.

The previous Annex IV report (Copping et al. 2013) concluded the following:

- Nearfield changes are not likely at the small pilot scale, but could occur at a large scale.
- It is not known if a tipping point exists for farfield changes that might affect the overall waterbody.
- Researchers need better measurements of turbulence and inflow to devices to estimate environmental changes.

5.5 KNOWLEDGE GENERATED SINCE 2013

In scouring the scientific literature, two additional field studies were found that address changes in physical systems in the presence of tidal turbines, along with one additional laboratory study, seven additional tidal energy modeling studies, and three additional wave energy modeling studies. These studies deal explicitly with the environmental effects of the MRE devices, as opposed to many more studies published that examine aspects of turbine or WEC performance, reliability, and design. The following is a list of studies included, in the order of appearance:

- Influence of Varying Tidal Prism on Hydrodynamics and Sedimentary Processes in a Hypertidal Salt Marsh Creek (O'Laughlin and Proosdij 2013)
- Flocculation and Sediment Deposition in a Hypertidal Creek (O'Laughlin et al. 2014)
- Effects of Energy Extraction on Sediment Dynamics in Intertidal Ecosystems of the Minas Basin (van Proosdij et al. 2013)
- Impact of Scaled Tidal Stream Turbine Over Mobile Sediment Beds (Ramírez-Mendoza et al. 2015)
- Tidal resource extraction in the Pentland Firth, UK: Potential impacts on flow regime and sediment transport in the Inner Sound of Stroma (Martin-Short et al. 2015)
- Impact of Tidal-Stream Arrays in Relation to the Natural Variability of Sedimentary Processes (Robins et al. 2014)
- Modeling of In-Stream Tidal Energy Development and its Potential Effects in Tacoma Narrows, Washington USA (Yang et al. 2014)
- Impacts of Tidal Energy Extraction on Sediment Dynamics in Minas Basin, Bay of Fundy, NS (Smith et al. 2013)
- Modeling the Effects of Tidal Energy Extraction on Estuarine Hydrodynamics in a Stratified Estuary (Yang and Wang 2015)
- A Modeling Study of the Potential Water Quality Impacts from In-Stream Tidal Energy Extraction (Wang et al. 2015)

- Sediment Transport in the Pentland Firth and Impacts of Tidal Stream Energy Extraction (Fairley et al. 2015)
- Wave farm impact: The role of farm-to-coast distance (Iglesias and Carballo 2014)
- Wave farm impact on the beach profile: A case study (Abanades et al. 2014)
- Possible Impact on Hydrography and Sediment Transport by Wave Power Park – Numerical Modelling (Persson 2009)

The environmental oriented studies are described in the following section.

5.5.1 FIELD STUDIES

No new studies have measured conditions pre- and post-installation of MRE devices. However, research in the Bay of Fundy used natural variability as a proxy for the perturbations caused by tidal devices and looked at changes in sediment transport in tidal creeks.

Data in a Bay of Fundy salt marsh examined the effects of energy removal from the system on sediment dynamics and deposition within the creek over 18 tidal cycles. The researchers used instrument packages with ADVs (acoustic Doppler velocimeters), optical backscatter sensors, a bottom-mounted acoustic Doppler current profiler (ADCP), sediment traps (as seen in Figure 5.1), and standard oceanographic instruments to provide context for the measurements (O'Laughlin and Proosdij 2013; O'Laughlin et al. 2014). The researchers found that a decrease in the tidal amplitude due to energy removal by tidal turbine arrays may decrease the cumulative export capacity of tidal channels over time, potentially leading to a gradual infilling of tidal creeks.

Figure 5.1 Example of sediment trap filters used from Starrs Point, in the Bay of Fundy. Sediment traps are placed on the surface of intertidal mud flats and measure sediment deposition under different tidal cycles (from van Proosdij et al. 2013).

Similar field studies conducted over 73 tidal cycles at nearby intertidal sites in the Bay of Fundy assessed the dynamics of sedimentation change in response to changes in energy between neap and spring tidal cycles, as an analogue to the impacts of tidal energy extraction (van Proosdij et al. 2013). Sediment deposition appeared to be most sensitive to changes in water depth rather than changes in tidal energy, because the inundation of high marsh areas contributed significantly to the available sediment in the system. Reduced tidal amplitudes may also reduce sediment mobility during ebb tides, causing creek infilling and a reduction in bank steepness.

Field studies will yield better understanding when measurements around device arrays are available. But until that time, proxy measures for changes in flow and energy removal provide insight into the potential effects of MRE development.

5.5.2 LABORATORY STUDIES

In the same way that proxies can be used to estimate effects in the real world, understanding energy removal from marine energy devices can begin with laboratory experiments. The complexities of the real-world marine environment can make it difficult to determine potential effects, but variables can be controlled in a laboratory setting and allow researchers to isolate specific effects of interest.

Tidal turbines are expected to increase erosion near the rotor, suspend sediments, and transport those sediments downstream. A turbine array may further transport sediments, but the direction of transport may be reversed with change in the tidal flow. To better understand these mechanisms, a series of experiments were carried out in a 16 m long flume with a scaled turbine and a mobile artificial sediment bed to simulate real field conditions (Ramírez-Mendoza et al. 2015). Velocity was decreased in the entire water column and no flow recovery was recorded after 12.5 diameters downstream from the turbine. An erosion area with a horseshoe shape was generated near the turbine. These results reveal further details about the hydrodynamics and geomorphology of tidal turbines.

Naturally changing environments such as sediment distribution across a seabed can be very difficult to model and understand, which allows laboratory experiments to answer important questions about erosion and geomorphology (Ramírez-Mendoza et al. 2015). Results can be used to improve how well turbines are modeled and interact with the physical environment.

5.5.3 MODELING STUDIES – TIDAL ENERGY

Hydrodynamic models that simulate tidal energy removal have increased in complexity in recent years, with the use of more detailed grid systems, more complex and realistic energy removal modules, and more reliable input data. Most new modeling efforts are being developed in the public domain using open source codes, so that the results are more accessible to MRE developers, regulators, and other researchers. Until commercial arrays are deployed and operated for a period of years, no adequate validation data will be available to verify the results of tidal models. The following modeling papers are not a complete inventory of effort, rather they focus on those with calibration data and a validation approach.

Meygen will be the first commercial tidal array deployed worldwide, with an anticipated 1 MW array to be deployed in the near future, and plans for expansion up to 398 MW in the Inner Sound of Stroma, Pentland Firth, Scotland. To better understand the potential impacts on the flow regime and sediment transport, researchers simulated a large array (85 - 400 turbines) in the three-dimensional (3D) unstructured-grid fluid dynamics model Fluidity (Martin-Short et al. 2015). Results were calibrated against data from six tidal gauges and a fixed ADCP. The results indicate that arrays of this size have the potential to alter sediment transport in the nearfield close to the array and the surrounding area, showing sediment accumulation within the array and scour to the sides of the array. Effects in the farfield can be anticipated to be measureable with array development on the order of 200 MW.

Researchers assessed the potential effects caused by tidal energy extraction on the natural variability of sedimentary processes at a test site in the Irish Sea, off northwest Anglesey, UK (Robins et al. 2014). Two surveys were conducted in 2012; using Laser In Situ Scattering and Transmissometry to measure suspended sediment, calibrating the instrument with water, and collecting sediment grab samples. Bathymetric data were also collected to inform modeling efforts. Using TELEMAC, a finite-element morphodynamics model, and SISYPHE, a sediment transport model, the researchers simulated tidally induced bed shear stress along a depth-averaged two-dimensional (2D) unstructured grid. Results showed a reduction in regional velocities and sand accumulation in the array, which may alter the structure and maintenance of offshore sand banks, to a distance less than 10 km away. Output from the model must be considered in the context of localized natural processes, including the incident wave climate, occurrence of storm events, and seasonal effects on the ocean. Lower energy demands at high latitudes in the summer may coincide with periods when sediment processes are most sensitive, allowing MRE developers and regulators to benefit from the modeling outputs to alter operational characteristics to alleviate potential deleterious effects.

Tacoma Narrows in Puget Sound, Washington, in the United States, has been analyzed by developers as a potential tidal energy site. Using the Finite Volume Coastal Ocean Model (FVCOM), a 3D unstructured-grid (as seen in Figure 5.2) finite volume coastal ocean hydrodynamic model, researchers developed tidal energy extraction modules for a 10 m diameter horizontal-axis gravity-mounted turbine for Puget Sound and surrounding waterbodies (Yang et al. 2014). A momentum sink approach was used to simulate 20, 50, and 100 turbines, with 30-day average extractable power of 1.21 MW, 2.93 MW, and 5.48 MW, respectively. Results showed measureable effects on the velocity field and bed shear stress in the immediate area of the tidal turbines. At the local scale, this may translate to changes in water quality, contaminant transport, and sediment dynamics.

Researchers in the Bay of Fundy, Nova Scotia, Canada, addressed sediment erosion/accretion in the presence of tidal energy extraction, as the system adjusts to a new equilibrium (Smith et al. 2013). Using well-established 3D hydrodynamic models (Delft3D and FVCOM), and unstructured mesh cells, the researchers simulated differences between spring and neap tide conditions as a proxy for tidal energy extraction in Minas Basin to evaluate sediment erosion, suspension, transport, and deposition. The model outputs indicated that tidal velocities at the turbine sites would be decreased by 10 - 20%, while tidal current speeds would increase outside the array along the northern and southern coast-

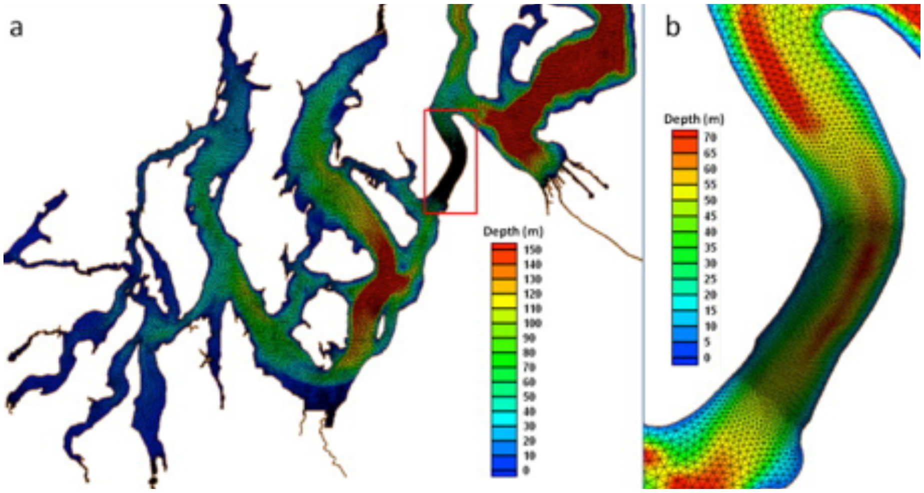

Figure 5.2 Example of an unstructured grid overlaid with bathymetry in the (a) South Puget Sound, Washington, USA and (b) Tacoma Narrows. Many models use unstructured grids to better follow the shoreline and to easily transition into higher resolution in the area of interest (from Yang et al. 2014).

lines of Minas Passage. These changes would result in less movement of coarse sediment in the central basin of Minas Passage and more coarse sediment being directed into a coastal bay.

A variety of turbine configurations were modeled in an idealized stratified estuary, connecting to coastal waters through a narrow tidal channel, in order to investigate changes in temperature, salinity, and velocity profiles (Yang and Wang 2015). The unstructured-grid coastal ocean model FVCOM was used with inputs emulating real-world values seen in Puget Sound. Results show a tidal phase shift on both the bottom and surface currents; increased vertical mixing will weaken the stratification and two-layer circulation in the estuary. The greatest impact is seen during neap tides when tidal mixing is weakest and energy extraction is smallest. Relatively small impact was seen; energy extraction values were less than 10% of the total available energy.

The same idealized estuary was modeled to directly assess the potential effects on water quality resulting from tidal energy extraction (Wang et al. 2015). A modified nitrogen-based, water-quality model was linked to FVCOM to simulate phytoplankton, zooplankton, nitrate, ammonium, detrital nitrogen, detrital carbon, and dissolved oxygen (DO). Results show that energy extraction can cause decreased flushing and increased vertical mixing in the channel that can directly affect water-quality responses in the estuary. Increased vertical mixing can have positive effects by causing higher concentrations of bottom water DO at times, but decreased flushing can deleteriously affect water quality by increasing phytoplankton production and decreasing bottom water DO concentrations. These impacts are directly proportional to the amount of power extracted; significant extraction is required to achieve measurable changes.

No study to date has assessed sediment impacts from multiple arrays in close proximity. As multiple projects are being planned in the Pentland Firth, a sediment transport model assessed four separate arrays in close proximity, with the total capacity of 481 MW (Fairley et al. 2015). Lacking comprehensive data, grain size was interpolated between ship-mounted grab sediment samples, while mobile sediment was defined based on multibeam echosounder data that was ground-truthed with video surveys. The hydrodynamic and sand transport modules of the MIKE3 suite were used on an unstructured triangular mesh with stretched sigma layers. Three ADCPs were deployed to validate currents, though some over-prediction was seen. Some arrays showed no significant effects, while others showed noticeable changes to both residual transport directions and magnitudes, highlighting the importance of array siting.

Numerical models simulating changes in the physical environment caused by tidal energy extraction have been improving with the use of practical numbers of turbines (Yang et al. 2014; Martin-Short et al. 2015), more accurate modeling of sediment transport processes (Robins et al. 2014; Smith et al. 2013; Fairley et al. 2015), and the inclusion of water-quality constituents (Yang and Wang 2015; Wang et al. 2015). Models are likely to continually advance as measurement techniques and computer power improve. The unique ability for models to separate changes caused by the introduction of marine devices from natural variability will continue to prove valuable as the MRE industry expands.

5.5.4 MODELING STUDIES – WAVE ENERGY

Few new numerical models that address energy removal by WECs have been developed in recent years, but new applications of the key model, SWAN (Simulating WAves Nearshore), are being used to approach questions of environmental significance.

Researchers from the UK and Spain modeled 10 floating overtopping WaveCat devices off the coast of Galicia, Spain, using SWAN in a nested grid at varying distances from shore (Iglesias and Carballo 2014). The study used experimental data to determine interactions between the devices and developed wave transmission coefficients from laboratory flume tests (Fernandez et al. 2012). Model results indicate the total energy focused on the nearby shoreline does not change with the distance the WEC array is located offshore, but that increasing the deployment distance offshore can reduce the concentration of energy directly shoreward from the array.

A case study at Perranporth Beach, Cornwall, UK, was used to examine the impact of a WEC array on the beach profile (Abanades et al. 2014). Wave propagation was modeled using SWAN and beach profile evolution was modeled using XBeach. The wave farm consisted of 11 WaveCat devices, which reduced the wave energy flux by up to 12% (as seen in Figure 5.3). This relatively small array was shown to have a significant effect on reducing the erosion of the beach face, indicating that wave farms may be useful as a coastal defense measure. Future research will need to focus on quantifying the level of protection that will be achievable.

The possible impacts on hydrography and sediment transport caused by 60 point absorbers was investigated (Persson 2009). A hypothetical wave farm was modeled with three flat bathymetries of varying depth, using sea-based devices comprising a linear generator attached to a surface buoy, line, and bottom-mounted foundation. Hydrodynamic and mud transport modules from the MIKE21 flow model were used to produce a 2D model with an unstructured triangular grid. The scale of impact was shown to be fairly local, and a farm of this size is unlikely to strongly influence the marine environment.

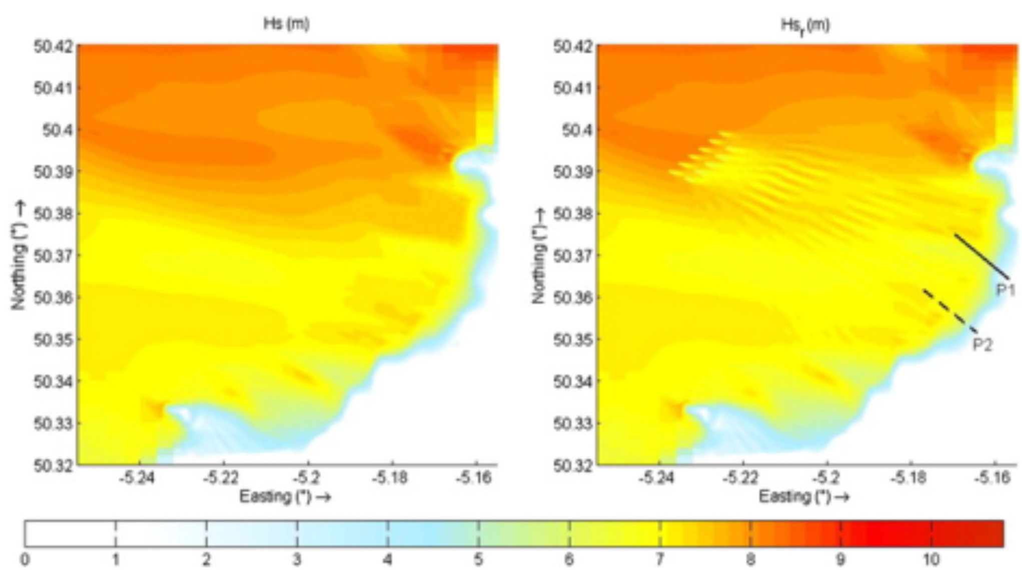

Figure 5.3 Example of modeling that shows the reduction in significant wave height from the baseline (left) to a scenario with a small wave farm (right) at the peak of a storm event. A substantial decrease in wave height that exceeded 30% was observed in the wake of the devices. This demonstrates local energy removal effects from devices that may impact sediment transport (from Abanades et al. 2014).

Numerical models simulating changes in wave energy extraction systems have looked for impacts on the nearshore areas, particularly the focusing of energy nearshore that could cause changes in shorelines (Iglesias and Carballo 2014) and beach erosion profiles (Abanades et al. 2014). Meanwhile other simulations focus on simplifications in order to better understand the specific interactions between the device and the environment (Persson 2009). The complexity of wave regimes and variety of WEC devices will continue to challenge wave modelers, but they have the potential to assist the MRE industry with cost-effective planning and simulation of environmental effects.

5.6 DISCUSSION AND IDENTIFICATION OF DATA GAPS

Describing the changes that may occur in coastal and estuarine waterbodies where MRE development is proposed is theoretically feasible, particularly with the use of high-fidelity numerical models. In practice, measuring those changes and predicting their possible effects on water constituents like dissolved nutrients, dissolved gases, sediments, and planktonic organisms, is much more difficult. Modeling results indicate that the numbers of MRE devices deployed in an area must be very large to affect changes in flow and/or to create measurable effects of energy removal on a changing system. For this reason, regulators and stakeholders are becoming more comfortable with the likelihood that small numbers of devices will not change water quality, marine food webs, and other important ecosystem features. However, modeling outputs are of great value in providing illustrative assurances to regulators that energy removal by MRE harvesting does not pose a risk to the environment. As greater numbers of MRE devices are deployed in commercial arrays, increased efforts to model the potential outcomes, coupled with field measurements to validate the models, can help guide responsible deployment of arrays. Preliminary analyses (Yang et al. 2014; Yang and Wang 2015; Wang et al. 2015) indicate that tidal farms with 100 turbines or less have very little system-wide effects even in the most complex marine systems—making changes to the physical system less of a concern than more direct impacts such as animal collision and acoustic interference with animal navigation.

Comparing changes to the physical system with more direct impacts on animals highlights the lack of understanding of the true impacts of these changes. Physical changes have the potential to trigger second-order effects in populations and food webs that could have a greater impact. Yet, the marine system is always experiencing constant change and adapts to meet new stressors. Some researchers are instead looking at potential positive impacts, such as coastal protection from the strategic placement of MRE devices (Abanades et al. 2015). Projects such as the Mutriku Wave Power Plant (as seen in Figure 5.4) integrate wave energy devices into a breakwater (Torre-Enciso et al. 2009). A better understanding of changes to the physical environment could not only negate negative impacts, but could also lead to positive benefits.

Figure 5.4. The Mutriku Wave Power Plant opened in July 2011 and provides harbor protection while generating electricity by harnessing air compressed by the action of waves, showing a positive benefit of MRE devices. The plan has 16 turbines with a total capacity of 296 kW (Ente Vasco de la Energía, *http://www.eve.eus/Proyectos-energeticos/Proyectos/Energia-Marina.aspx?lang=en-GB).*

In the early stages of siting an MRE project, developers typically measure physical parameters in the ocean system to determine the power potential, survivability of devices, and potential for array optimization. Yet efforts to determine the signal within the noise of natural ocean variability, and to simulate future conditions under climate change and other factors, requires that very large data sets be collected and managed (Petrie et al. 2014). The data collection, storage, and management of these data sets will rapidly begin to overwhelm most investigators' abilities to process and interpret the information (Polagye et al. 2014). Increased emphasis on parameters of oceanographic and biological relevance such as water-quality and sedimentation parameters could help to advance the level of knowledge in this area.

There continue to be significant challenges to fully understanding and evaluating the potential effects of MRE devices on natural systems. The 2013 Annex IV report (Copping et al. 2013) listed five challenges that remain unanswered:

- **Validation.** Field measurements are needed for model validation to ensure that modeling simulations are accurate and reliable. Coordinated monitoring around full-scale deployments will overcome this challenge.
- **Turbulence.** Targeted research on turbulence, often collected for power optimization and survivability purposes for MRE projects, must be appropriately collected to inform numerical models that seek to measure potential environmental effects. Without turbulence measures, uncertainty around interpretation of environmental effects can be confounded.
- **Device Design.** MRE devices come in many different designs, scales, and operational modes, including many different WEC types and designs. Energy removal and flow changes affecting numerical simulations of systems have been developed for very few tidal turbine designs and even fewer WECs, yet potential environmental effects may depend very heavily on these differences. Targeted research must consider design specifics in modeling efforts, as opposed to simplifications such as momentum sinks.
- **Distance Scales.** Most modeling efforts for energy removal consider either the effect immediately around the MRE device (nearfield) or effects on large ocean areas (farfield). However animal populations and ecosystem processes do not recognize these distinctions and often are governed by linkages between these scales. Monitoring and resulting modeling efforts need to consider the linkages to all scales of the ocean area potentially affected—nearfield and farfield.
- **Cumulative Effects.** The present state of the MRE industry has not allowed for measurements of cumulative effects of many MRE farms in a region, nor the effects of MRE devices against a background of other anthropogenic effects on the marine environment. Models need to begin to incorporate these wider scale effects in order to accurately simulate future deployment conditions.

Research has advanced understanding of these challenges over the last three years, but these same issues remain major hurdles. Until more devices and arrays are in the water and actively collecting monitoring data for validation, the realism of these models will continue to be questioned. Meanwhile, challenges with device design, distance scales, and cumulative effects raise questions about the meaning and impact of model results. Understanding the environmental impacts of MRE devices will be a long process; the last several years have shown that this area of research still faces the same challenges as before.

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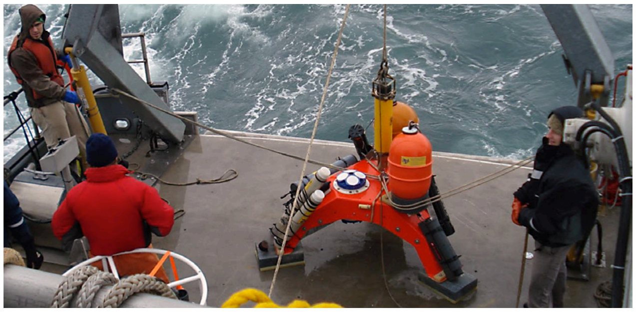

Chapter author: A. Gill

Effects of EMF on Marine Animals from Electrical Cables and Marine Renewable Energy Devices

To meet the objectives of the Annex IV, Phase 2, State of the Science report, this chapter focuses on the topic of electromagnetic fields (EMFs). EMFs are poorly understood and are conceptually a challenge to understand, perhaps because our inability as humans to sense them leads to less focus on EMF as environmental risks.

This chapter aims to identify the key questions that have arisen from various sectors in relation to EMFs and to provide an up-to-date synthesis of the current knowledge base. With this knowledge, the reader should be able to better appreciate EMFs as an environmental effect that should be taken into account when considering the sustainable management of human activities within the marine environment and promoting MRE.

The basis for the information used in the chapter primarily comes from peer-reviewed journal articles and book chapters and, owing to the paucity of information, industry-relevant reports, some of which have also been peer-reviewed. In addition, recent findings are included from a European research project that aimed to address some of the key information gaps related to EMFs associated with MRE devices.

To address the topic it is necessary to consider 1) the existing evidence base, 2) how this evidence has been produced, and 3) what the current state of the science is in terms of the effects of EMFs from marine cables on marine animals. The chapter focuses on addressing key questions surrounding EMFs. In order to do so the evidence has been separated into understanding derived from field studies, supplementary knowledge from laboratory studies, and any modeling studies based on extrapolation of field and laboratory studies.

The ensuing chapter sections provide the following information:

- background on EMFs, in terms of what they are and how they are defined, also how they occur in the environment;
- discussion of the existing knowledge about EMFs that is associated with MRE devices and a summary of the types of known species that are receptive to EMFs;
- a review of the existing literature on EMFs and the interaction with sensitive species, covering laboratory evidence, field studies, modeling, and a summary of the most recent empirical evidence;
- consideration of what the knowledge base means to date and where the topic should go in terms of addressing priority knowledge gaps;
- a suggested integrated approach for moving the topic forward that will require the industry, regulators, academics, and stakeholders to work together.

6.1 BACKGROUND FOR EMFS

Electromagnetic fields are always present in the environment around us, whether in air or in water. They are naturally occurring emanations from sources away from the Earth, such as the sun, and they are produced by the Earth's core, in the form of geomagnetic fields (see Figure 6.1).

In seawater the dominant source of natural electric fields is a consequence of the interaction between the conductivity of the seawater and the rotation of the Earth and the motion of tides/currents (Stanford 1971) creating localized EMFs, known as motionally induced fields (Figure 6.1). This context is important when asking questions about EMFs associated with MRE devices because it sets the scene for a natural EMF environment within which many organisms that are known to be sensitive to EMF have evolved.

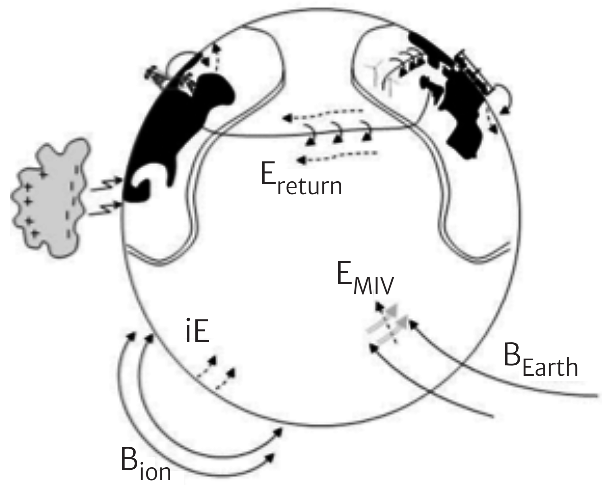

Figure 6.1. Representation of natural and anthropogenic sources of electric (E) and magnetic (B) fields associated with the Earth. The B-fields penetrate or are generated in the sea and the E-fields (*dashed arrows*) are induced by the B-fields (*solid arrows*). BEarth is Earth's magnetic field; B_{ion} are magnetic fields from the ionosphere; E_{MIV} is the motionally induced voltage electric field; E_{return} is electric field from subsea cable return current fed through the sea (from Gill et al. 2014)

The Earth's magnetic field is the dominant natural source of magnetic field in the sea (and on land); it has a strength of approximately 30 microtesla (μT) at the equator and about 60 μT at the poles. The second most significant magnetic source is associated with energetic particles coming from the sun. The flux of the particles collides with the Earth's upper atmosphere, creating electric currents in the ionosphere resulting in variable magnetic fields, which then propagate to the Earth's surface and into the sea. The magnetic field has a strength of about 1–10 nanotesla (nT) at the Earth's surface on days of low solar activity (Gill et al. 2014).

When asking questions about the EMFs associated with MRE devices, it is important to superimpose such anthropogenic sources of EMF onto existing EMFs (whether they are natural or human-related emissions). Human activity in the sea inevitably creates potential sources of EMF, such as electrical cabling systems. Conceptually, it is evident that EMFs exist in the marine environment, and predictive modeling of EMFs emitted by subsea cables also provides evidence that EMFs should be present and the varying extent of the emissions is associated with different cable types (Figure 6.2; from Normandeau et al. 2011). However, it is necessary to know first whether MRE devices emit any detectable EMFs into the marine environment and if there are, the crucially important question is whether these emissions are of biological relevance.

Based on the general physical properties of EMFs, it is expected that EMF field strength will decay as it propagates away from the source (see Figure 6.2). The propagation is perpendicular to the axis of the cable and the inverse form of the propagation will depend on the power within the cable and the cable characteristics (Figure 6.2). If the cables are separated a bimodal EMF is present (Figure 6.2). Furthermore, the EMF will be present along the length of a cable, cycling back and forth at 60 cycles per second for a 60 Hz alternat-

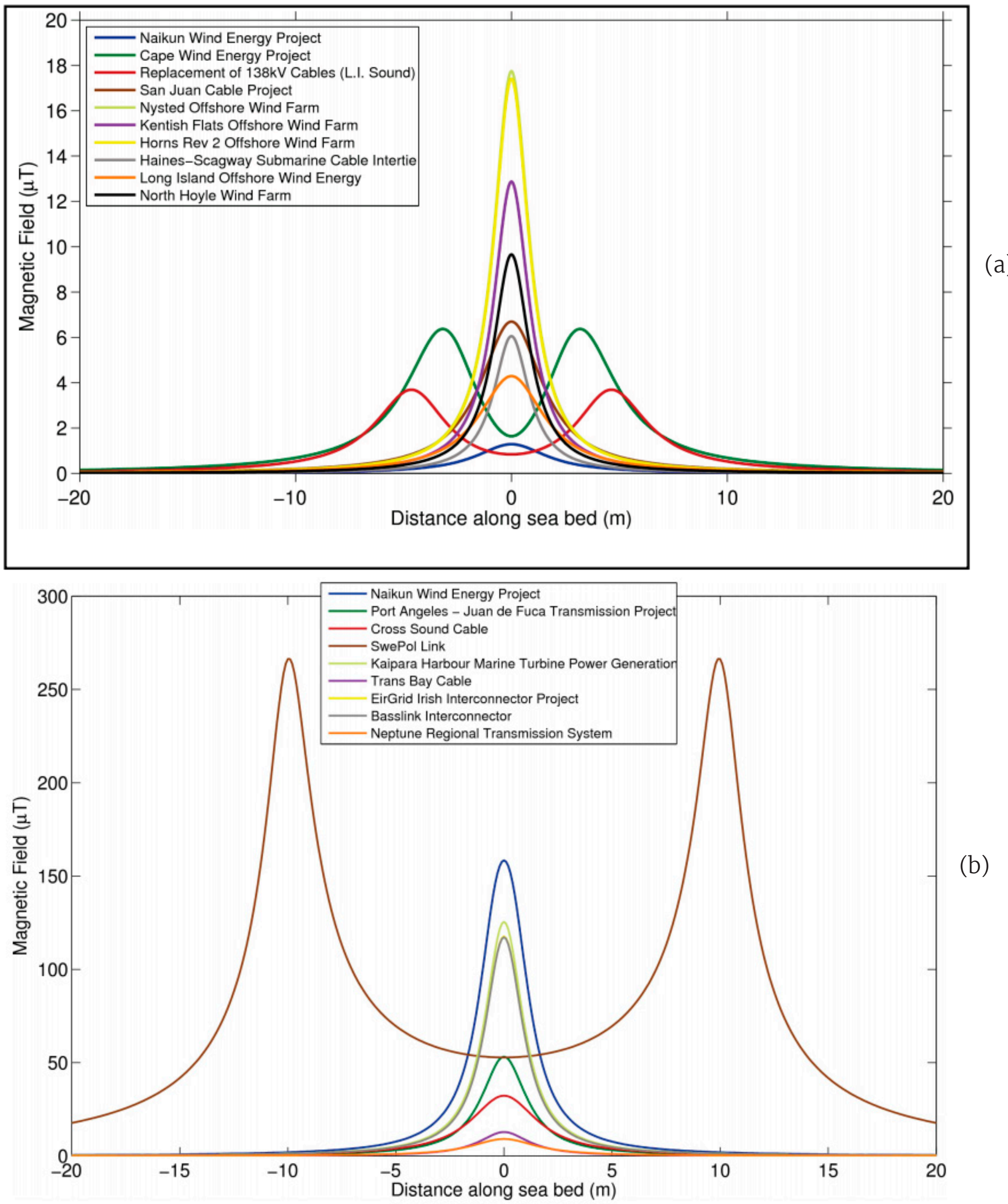

Figure 6.2. Modeling predictions of EMF emitted by existing cables at different sites across the world. (a) AC cables with different characteristics, (b) DC cables with different cable characteristics and layouts creating the different predicted emissions (from Normandeau et al. 2011).

ing current (AC) cable, or a continuous static emission along direct current (DC) cables when energized. Thus, the EMF will cover volumes larger than the source itself. So electric cables will create a long area of emission, and thus could theoretically constitute a potential barrier to movement for sensitive species.

According to current industry specifications, the cables used inside tidal, wave, and wind energy arrays carry AC power. The most common AC cable used is 3-phase (i.e., has three conductors within one cable). The field strength of the magnetic and electric fields generated depends on the amount of electrical current in the cable and the distance between the conductors as well as the balance of the load between the three phases in the cable. Other factors that influence the strength of the fields are the magnetic shielding of the cable and the relative position between the conductors in the cable (i.e., the symmetry of the triangular geometry of the three conductors).

Familiarity with EMFs can be improved if they are clearly defined. In the field of physics two magnetic fields can be determined: the magnetic flux density, known as the B-field, and the magnetic field intensity, denoted by the H-field. In nonmagnetic environments, such as the sea, the magnetic field tends to be referred to in terms of the B-field. The B-field is measured in tesla (T) in SI units and in gauss (G) in CGS (centimeter–gram–second) units (1 tesla = 10,000 gauss). The physics of the fields are described by Maxwell's equations that are used to describe how an alternating electric current produces both magnetic and electric fields; while a stationary current (DC) produces only magnetic fields directly. The electric field, abbreviated to E-field, is measured in volts per meter (V/m). In environmental sciences the term induced-electric field (iE-field) is used to highlight that this type of E-field is caused by magnetic induction (see Figure 6.3). The iE-field is also expressed in V/m.

Figure 6.3 provides a simplified overview of the fields and their association with industry-standard submarine power cables, highlighting the magnetic and iE-fields that are of interest to the present topic.

When considering the effects of EMF from electrical cables and MRE devices on marine animals, knowledge of the EMF as a source of potential effect is fundamental. This background can then be used to contextualize the electromagnetic (EM) environment in which receptor organisms are immersed in the marine environment.

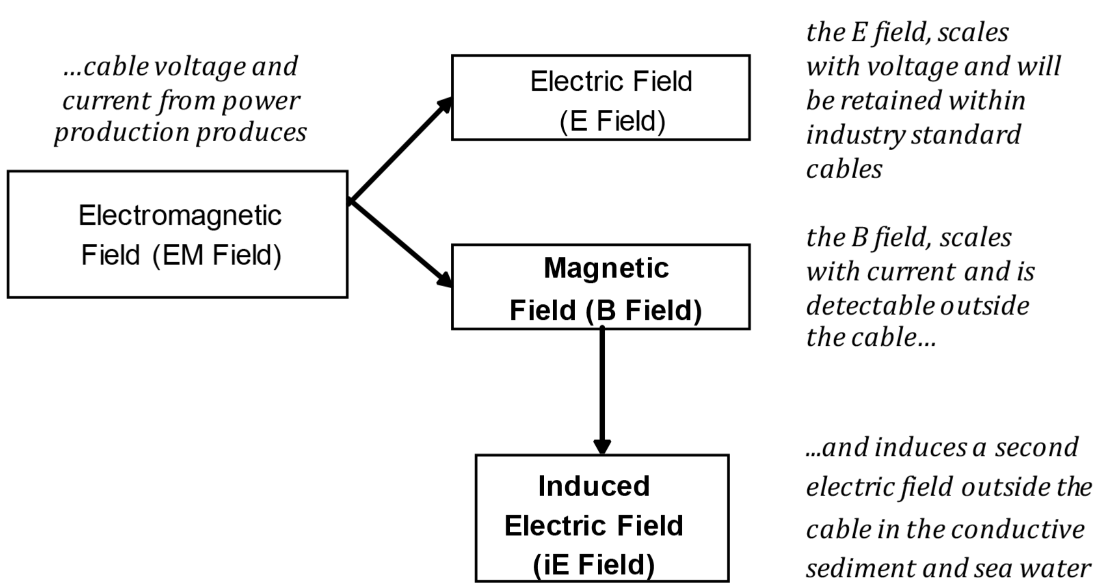

Figure 6.3. Simplified overview of how induced electrical fields are produced by AC-power cables (adapted from Gill et al. 2009)

6.2
ANTHROPOGENIC EMFS FROM MRE DEVICES

The main objective of MRE devices is to produce electric power, hence all MRE devices have a variety of EMF-emitting sources. The dominant sources are the electric cables, usually buried or on the seabed, which have inter-device cables running inside the renewable energy array and the export cable(s) that connect the MRE device to the land-based power grid (Öhman et al. 2007; Schachner 2001; Figure 6.4). The electromagnetic emissions created by these two types of transmissions are very different. An AC generates a time-varying magnetic and electric field (B-field and iE-field), while a DC only generates a static magnetic field (B-field; Öhman et al. 2007). Any movement through the magnetic field (e.g., tidal water movement or a swimming animal) will induce electric fields in the local environment or within the animal. A general rule concerning the power output from an MRE device is that the higher the electrical current the stronger the emitted magnetic field and iE-field will be for AC cables. For DC cables the magnetic field will be stronger, and there is no directly emitted electric field. It is important to note that the EMF associated with an MRE device requires not only detailed knowledge of the device(s) and the cables, but also the electric design (topology) of the array, as suggested by Figure 6.4. Because they are required to transmit higher power, the export cables can be either AC or DC cables.

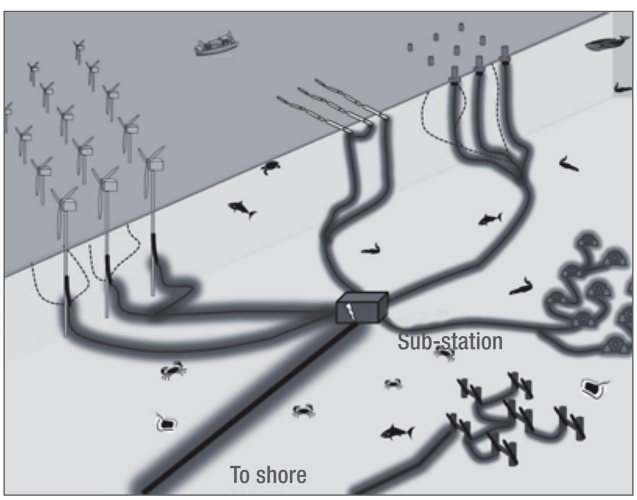

Figure 6.4. A hypothetical schematic of different marine power-producing technology arrays and the associated EMFs represented by the grey zone on either side of the solid lines (not to scale). The cables running between the devices and the substation are lower powered (indicated by the thin solid line) than the export cable, which is high powered (indicated by a thick solid line) (from Gill et al. 2014).

6.3
EMF-RECEPTIVE MARINE ORGANISMS

The ability to sense and respond to EMFs is surprisingly common in marine organisms, which comprises many sensitive species from very different taxonomic groups, ranging from microscopic bacteria to megafaunal whales. The groups that tend to be focused upon are the larger bodied fauna, namely:

- elasmobranchs (sharks, skates and rays),
- agnatha (lampreys),
- crustacea (lobsters and prawns),
- mollusca (snails, bivalves, cephalopods),
- cetacea (whales and dolphins),
- bony fish (teleosts and chondrosteans), and
- marine turtles.

The majority of these animal groups are considered magnetoreceptive, principally in relation to local-scale orientation or large-scale navigation within the marine environment (Kirschvink 1997). Animals that are sensitive to electric fields (Peters et al. 2007) are considered able to detect E-fields whether directly emitted or induced via magnetic fields (Gill et al. 2014).

In terms of magnetoreception, and based on up-to-date understanding, the majority of receptive animals use a magnetite-based sense, also known as photoreceptor-based sense (Kirschvink 1997; Solov'yov et al. 2010). While still to be definitively proven, it is generally accepted that magnetoreceptive animals use magnetic cues for orientation and navigation, and the most widely known source is the Earth's geomagnetic field (Walker et al. 1992; Kirschvink 1997).

Fewer taxa of marine animals are electrosensitive; elasmobranchs (sharks, skates and rays) are the most numerous and widespread and considered to be likely to respond to the E-fields they encounter, owing to their sensitivity (lowest known detection thresholds of 5 – 20 nV/cm; Kalmijn 1982; Tricas and New 1998; Bedore and Kajiura 2013).

Electroreception and magnetoreception do not necessarily operate on their own; they are used by organisms in conjunction with other sensory abilities (e.g., auditory, visual, or olfactory cues; Kirschvink 1997; Peters et al. 2007; Solov'yov et al. 2010), but they are recognized as playing an important role at some times in the lives of sensitive species.

Organisms that are known (or presumed) to have the ability to detect magnetic fields are categorized into two groups based on their mode of B-field detection: magnetite-based detection and iE- detection.

The first mode relates to magnetite deposits within the body (most commonly the anterior end of the organism) that play an important role in geomagnetic field detection in a large variety of organisms. For many species the sensitivity to the geomagnetic fields is associated with an ability to determine direction.

The second mode is associated with species that are electroreceptive, the majority of which are the elasmobranchs. Generally, it is assumed that species use the iE-field mode for navigation and this can be either:

- passive – the animal estimates its movement through the water from the electrical fields produced by the interaction between tidal and wind-driven currents, and the vertical component of the Earth's magnetic field; or
- active – the animal derives its magnetic compass heading from the electrical field it generates by its body interacting with the horizontal component of the Earth's magnetic field.

Organisms that are known (or presumed) to have the ability to detect electric fields have specific sensory cells known as Ampullae of Lorenzini, that respond to very low-frequency E-fields. The sensory cells are connected to the surface of the animal via conductive canals that end in open pores at the surface of the animal (Tricas and New 1998; Peters et al. 2007). The position of the cells and the length of the canals play an important role in the sensitivity to the E-fields and the locating of the source of the EMF.

6.4 CONSIDERATIONS IN RELATION TO ANTHROPOGENIC EMFS

When considering the potential effect of EMF on marine organisms the anthropogenic generated levels need to be compared to both natural ambient fields and any other anthropogenic EMFs that are present in the area prior to the deployment and operation of the MRE device(s) (Figure 6.1). Furthermore, the general approach in environmental assessment (if EMF is included for consideration) is to assess species avoidance aspects. However, it is equally important to also consider attraction to EMF sources given the emissions are within the detection range of the few species that are known to be EM-sensitive.

While organisms' magnetic abilities are generally linked to the Earth's geomagnetic field, some have been shown to respond to artificial magnetic fields; hence, it is not unreasonable to suggest that they may have the potential to detect and respond to the magnetic fields emitted by subsea cables. Therefore, the potential exists for cable B-fields to interfere with migratory movements of animals primarily because of a perceived barrier effect (Tesch and Lalek 1973; Westerberg and Begout-Anras 2000; Westerberg and Lagenfelt 2008), particularly for species of conservation concern (such as migratory fish, marine mammals, turtles, and crustaceans). Alternatively, in addition to a B-field causing a barrier effect, magnetosensitive species may be attracted to or diverted along cables (e.g., European eels; Westerberg and Lagenfelt 2008).

Studies have been undertaken to understand whether anthropogenic magnetic fields have any effect on sensitive species. Such studies have tended to use artificially created magnetic fields (usually a localized field from a magnetic coil) to demonstrate some response in receptive animals at B-fields either greater or less than the ambient Earth's magnetic field intensity (approx. 30 – 60 μT depending on geographic latitude; Meyer et al. 2005). The interpretation of whether the B-fields will have any effect on receptive species has generally been that there is unlikely to be any associated impact if the anthropogenic source is at or below the geomagnetic intensity or ambient conditions (Gill et al. 2014).

When considering electroreceptive species, their ability to detect the very low-frequency, natural bioelectric fields emitted by living organisms, allows them to either hunt for prey, find mates, or avoid predation (Tricas and Sisneros2004; Peters et al. 2007). Based on current evidence, electroreceptive animals use the changing gradient of intensity of electric fields to home in on the source, thereby acting like an attractant within threshold levels approximately between 5 nV/m and 1000 μV/m (Kalmijn 1982; Tricas and New 1998; Peters et al. 2007). Elasmobranchs have been shown to be repelled by strong anthropogenic E-fields (e.g., electric shark repellents; Huveneers et al. 2013), which has led to questions about whether cables inducing electric fields may act as barriers to elasmobranch movement (e.g., between feeding, mating, and nursery areas). However, the evidence to date, based on the power rating of cables currently used by industry, is that EMFs are unlikely to get to the upper levels of sensitivity where the animals may be repelled. The more likely outcome is that the EMFs are in the lower range and therefore provide an attractant stimulus to E-receptive species. Larger capacity cables capable of transmitting up to three times the power of existing cables (i.e., 400 to 600 kV carrying 1 to 2 kA) are being developed. Assuming that EMF scales comparably with cable size, there is the possibility of reaching the upper threshold between animal attraction and repulsion, in the future.

Studies linked to understanding whether electrosensitive species can respond to any source of anthropogenic EMF are few, so the evidence base is limited, at best. By extension, this means the evidence to apply to subsea cables and MRE devices is also lacking. In light of this, to determine the effects of EMF on receptive animals it is useful to consider the pathways that exist between the potential environmental stressor EMF and receptor animals, which may result in EM-receptive species being affected. Isaacman and Daborn (2011) developed a Pathways of Effect (PoE) model that clearly specifies EMF as a stressor, likely receptors, and the pathways of potential effect (see Figure 6.5).

Figure 6.5 categorizes the potential effects (yellow rounded boxes) on the different receptors (blue ovals) that have been identified as being associated with EMF emissions from MRE devices. These effects cover potential or hypothesized consequences for early life stages in terms of physiological and developmental effects, behavioral responses associated with predator-prey relationships, attraction to or avoidance of EMFs, and alterations in movement at the local scale (orientation) or large scale (migration). This PoE model from Isaacman and Daborn (2011) enables conceptualization and communication of the unfamiliar topic of EMF interactions with marine receptors. The next step is to consider the evidence base to enable judgment of the likelihood or plausibility of the potential effect on the receptors identified.

6.5 EVIDENCE BASE FOR EMF EFFECTS ASSOCIATED WITH SUBSEA CABLES AND/OR MRE DEVICES

Many fish receptors are considered capable of detecting E-fields and/or B-fields, but data on the effects of EMF from subsea cables on fish are currently inconclusive (Gill et al. 2014). Based on available information, the current evidence can be summarized as follows:

- E-sensitive species are potentially able to detect EMFs from both DC and AC cables and may have higher sensitivity to DC cables because of the lower frequency of the field emitted. The highest sensitivity taxa known are the elasmobranchs, the jawless fish (Agnatha), and sturgeons, paddlefish, and relatives (the chondrosteans) (Peters et al. 2007).
- Magnetosensitive species are likely to be able to detect EMFs from DC cables and potentially AC cables, but to a lesser degree owing to the expected lower magnetic emissions associated with AC cables (Normandeau et al. 2011).
- Behavioral responses of sensitive species to subsea cables have been demonstrated, but, based on current knowledge, it is not possible to extrapolate these studies to situations where there are networks of multiple cables, such as those associated with MRE devices (Gill et al. 2014). Furthermore, behavioral response to EMF from a cable (or multiple cables) is not sufficient to determine any impact unless significant biological consequences result (such as large-scale redistribution or population changes of sensitive receptors). Specific studies of the cable characteristics and the resultant EMF with respect to species response through time and spatial extent are required.

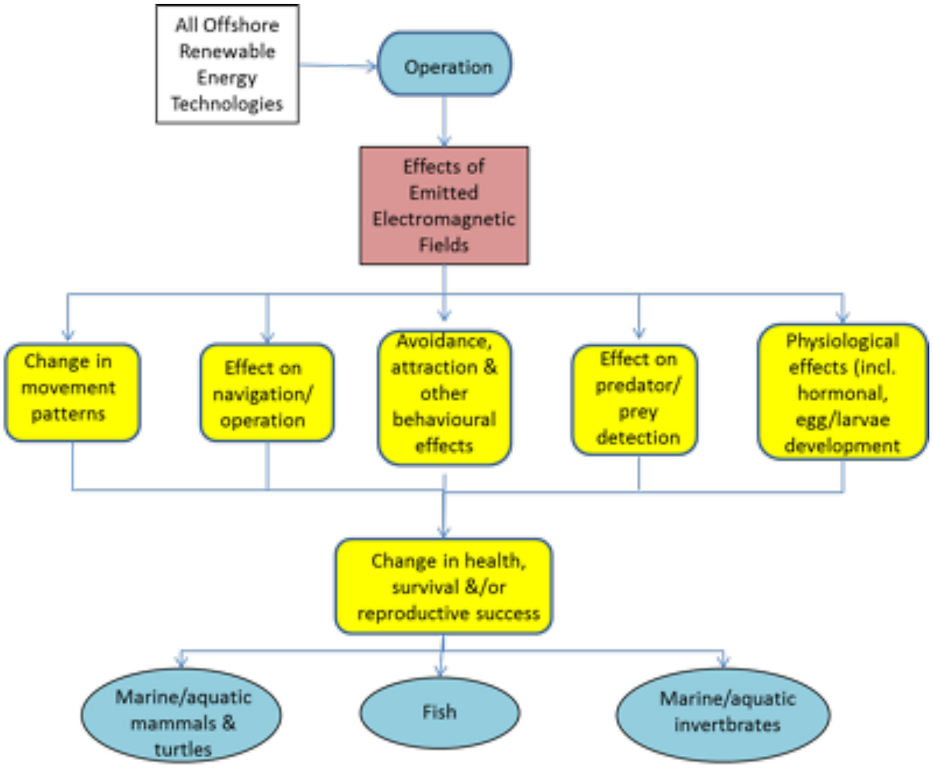

Figure 6.5. Pathways of Effect conceptual model for MRE device effects on receptor animals (redrawn from Isaacman and Daborn 2011)

- Benthic and demersal species are considered to be more likely to be exposed to higher field strengths than pelagic species, because the EMF is principally emitted by cables buried on the seabed or covered by protection on the seabed (Gill et al. 2014).

Recent, controlled laboratory studies by Woodruff et al. (2012) looked at the physiological and behavioral responses of fish (salmon and halibut species) to EMFs of the level expected from cables associated with hydrokinetic turbines. As with many laboratory studies, sample size and exposure duration create limitations in how to apply and interpret the findings without further corroborative evidence. The results from these experiments were generally equivocal but there were some indications of developmental, physiological, and behavioral responses to the EMFs over relatively long duration (days to weeks) of exposure to EMFs; none of these responses (listed below) were statistically significant:

- Coho salmon showed some decreased swimming activity.
- Hormonal tests did not suggest any stress, but decreases in melatonin levels in Coho salmon were observed.
- Rainbow trout eggs exposed to EMF of 3 mT showed some delays in their development.
- Atlantic halibut exhibited reduced growth and development when exposed to EMF of 3mT.
- No effects were noted for growth or development of California halibut.

The intensities recorded were high compared to the predicted intensities associated with existing subsea cables (see Normandeau et al. 2011), hence these responses would only be of potential relevance if larger powered cables that emit higher magnetic fields were used and the exposure times were longer than anticipated for such non-sessile species.

Experimental studies in a semi-natural setting using large enclosures demonstrated some response of elasmobranch species to simulated EMFs of the type and intensity associated with offshore wind turbine cables (Gill et al. 2009). The results were variable within and between species with Catsharks (*Scyliorhinus canicula*) being attracted to and reducing movement near the cable and Thornback Rays (*Raja clavata*) increasing movement and apparent searching behavior.

Behavioral responses associated with navigation and/or orientation to EMFs have been recorded with altered movement paths by salmonids, sturgeon, and European eels (Öhman et al. 2007; Westerberg and Lagenfelt 2008; Gill et al. 2012) and sharks (Gill et al. 2009; Öhman et al. 2007).

A field study is under way at Florida Atlantic University in the southeastern United States to accurately measure EMF emissions in the water column from live submarine cables, and to monitor and catalog potential responses of mobile marine animals to EMF levels using divers, mobile autonomous underwater vehicles, and fixed bottom-mounted surveys. Although no organismal responses have been observed or detected at this time, additional surveys are under way to provide more data and a more detailed evaluation of apparent sensitive species and group-specific trends (Dhanak et al. 2015).

Perhaps surprisingly, little consideration has been given to whether magneto receptive marine mammals and turtles might be able to detect and respond to EMFs from MRE devices and/or subsea cables (Gill et al. 2014), because they are able to respond to the Earth's geomagnetic field (Kirshvink 1997). The likely explanation is that the MRE device/cable EMFs are less intense than the geomagnetic field, so it is assumed that the animals are less likely to respond (yet this has not been demonstrated). Also, the focus for marine mammals and their interaction with MRE devices has been on the effects of underwater noise (see Chapter 4) and collision risk (see Chapter 3). Nevertheless, whether marine mammals and turtles respond to cable EMF remains an open question. If they did respond to cables then mammals and turtles would more likely detect EMFs from DC cables than from AC cables, because the former characteristically have static B-fields (similar to the geomagnetic field) and they are of higher intensity than the latter. The likelihood of exposure will also be a function of the depth of the water above the cable and the depth of swimming because field strength dissipates with distance.

Many invertebrate species have the capability to detect electric- and/or magnetic fields. There are only inconclusive data that associate the effects of EMFs from subsea cables on any invertebrate species. The following are apparent:

- Some species of decapods crustacean have electro- and/or magnetosensitivity.
- Electrosensitive species would be expected to potentially detect EMFs from DC and AC cables.
- Magnetosensitive species would be expected to potentially detect EMFs from both AC and DC cables but with higher sensitivity to the magnetic field emitted by DC cables.

A limited number of laboratory-based studies on invertebrates and EMF have been undertaken. Cameron et al. (1993) demonstrated magnetic fields (1 – 100 μT) potentially affect sea urchin embryo development. EMFs from an AC source have been implicated in cell damage and disrupted settlement in barnacle larvae and brine shrimp (Leya et al. 1999). Extended exposure to magnetic fields from a high-voltage DC underwater cable had no apparent effect on the survival or fitness of shrimp, isopods, crabs, and mussels (Bochert and Zettler 2004).

In laboratory experiments, Woodruff et al. (2012) studied the behavioral responses of Dungeness crab, a commercial fishery species, to EMFs with a maximum strength of 3.0 mT, which is representative of cables associated with hydrokinetic devices. Similar to the fish, there were indications that the crabs could detect and respond to high and periodic EMF intensities, but the studies did not provide conclusive evidence:

- There was a decrease in antennular flicking rate, which was used as a measure of EMF detection, but this decrease was not statistically significant.
- Antennular flicking rate reduced in response to food odor following a 20-hour exposure to 3 mT EMF, but this was not statistically significant. The authors interpreted this as affecting possible food detection.
- Over 3 days of exposure to EMFs, crabs spent less time buried in sand and increased their activities between buried, resting, and active.
- Some possible habituation was suggested after 48 hours.

Based on the evidence to date there is no demonstrable impact (whether negative or positive) of EMF related to MRE devices on any EM-sensitive species (Gill et al. 2014). An important point to make here, is that the majority of the limited studies that exist have focused on the behavioral responses by the receptor animal to the EMF. Clear responses of diversion away from migratory paths to follow a subsea cable have been reported (e.g., barrier effect of high-voltage DC [HVDC] subsea cables; Westerberg and Lagenfelt 2008), and other studies have indicated species attraction to the subsea cable source of the EMF (Gill et al. 2009; dependent on the species of the receptor and EMF type and intensity). There is no basis currently to extrapolate the findings from such studies to determining the significance of the effect, i.e., the impact (sensu Boehlert and Gill 2010).

The findings from the laboratory studies give variable indications of whether exposure to EMF has any implications for species. It appears that continued exposure to EMFs can in some cases potentially alter early life history development attributes (e.g., Woodruff et al. 2012). To determine whether these effects are actually biologically significant impacts there would have to be quantifiable changes in the ability of individuals to develop to maturity and then recruit to the adult population. So far, such evidence is far beyond current research efforts and hence beyond our understanding and evidence base.

The potential for EMF to cause an impact is considered most likely for organisms living on or near the seabed (e.g., eggs, larvae, benthic or demersal species), especially species with limited mobility or in critical habitat areas, because mobile species are able to avoid/move away from areas with EMFs if they need to.

6.6 UNDERSTANDING DERIVED FROM MRE DEVICE FIELD STUDIES

The separation of EMFs into the constituent parts of magnetic and electric field is useful when considering how EMFs are measured. For B-fields, there are several commercially available magnetometers, which vary in sensitivity and detection range. A simple fluxgate magnetometer is able to detect B-fields, but the user needs to consider the three axes of the field in order to understand properly the B-field extent and orientation. When looking at E-fields the picture is very different. Difficulties are associated with measuring the very small (but biologically relevant) E-fields, the type of electrode used, the spacing between the electrodes, and the interference that can come from the instrument itself. Only a few research institutes are known to have developed or are developing a suitable E-field sensor that can measure the three axes of the electric field component of EMFs associated with MRE devices, namely the Swedish Defense Research Agency (known as FOI), Oregon State University, and Florida Atlantic University. The sensors are based on a recording platform with electrode sensors that either sits on the seabed (a lander) or moves through the EMF by passive drifting, active pulling by a boat, or autonomously (autonomous underwater vehicle).

To date the only available data on EMF associated with MRE devices has been reported by the recently completed European Commission MaRVEN project (Environmental Impacts of Noise, Vibration and Electromagnetic Emissions from Marine Renewable Energy). This project was aimed at addressing some of the priority gaps in knowledge about EMF (among other energy emissions) associated with MRE devices by conducting field-based studies at MRE device sites (Thomsen et al. 2015). For measuring the EMF a bespoke electromagnetic system (The Swedish Electromagnetic Low-Noise Apparatus [SEMLA]), from FOI was employed at operational wind farms in Belgian coastal waters. SEMLA consists of a three-axial fluxgate magnetometer (which is used to measure the magnetic field) and a three-axial electrode system (which measures the electric field). These are mounted on a non-metallic structure that can be actively towed behind a boat or kept suspended from the side of a drifting boat.

Belgium has three operational offshore wind farms. The focus of the measurements was the subsea cables transporting electricity within the wind turbine array and the larger power rated export cables associated with the C-Power and Northwind wind farms connected to the land-based power grid.

Because no at-sea EMF measurements from an MRE device were known, MaRVEN had two objectives: measure the underwater EMF to demonstrate that it was possible to detect both magnetic and electric fields emitted by the subsea cable of an MRE device, and if the EMFs were measurable quantify them. Two EMF measurement methods using the SEMLA were used. The first relatively rapid technique suspended the SEMLA in the water and let it drift over the cable. The second more time-consuming method towed the SEMLA on the seabed across a cable to get as close to the cable as possible. The latter approach focused on the EMF levels in the benthic/demersal zone known to be inhabited by several receptor organisms. The field survey measured interarray cables, export cables, and EMF in close proximity to a transformer station.

6.6.1 MEASUREMENT OF FIELDS FROM INTERARRAY CABLES AT THE C-POWER WIND FARM

The SEMLA was suspended from the side of a small vessel at 6 m depth and the engine was switched off while the boat drifted. The water depth was 20 – 25 m with the cable buried approximately 1.0 – 1.5 m into the seabed. The electric current applied to the cable at the start of the measurement was 76 A and 56 A at the end during the sampling period from late July to early August 2015. The current in the cable was associated with a chain of five turbines that were all generating power. Figure 6.6 shows that both the E-field and B-field were observed and that the maxima were not detected at the closest approach to the wind turbine (compare the peaks in the red, green, and black graphs with the blue line, which shows proximity to the turbine). Hence, it appears that the fields generated by a turbine itself are small/negligible compared to the field generated by the infield cable.

The maximum detected fields were assessed against the best available map of the cable network, which indicated that the EMF measured was most likely generated by a cable connecting two turbines (Figure 6.7). The maximum electric field was 0.3 mV/m with a magnetic field of 4 nT. The signal content was dominated

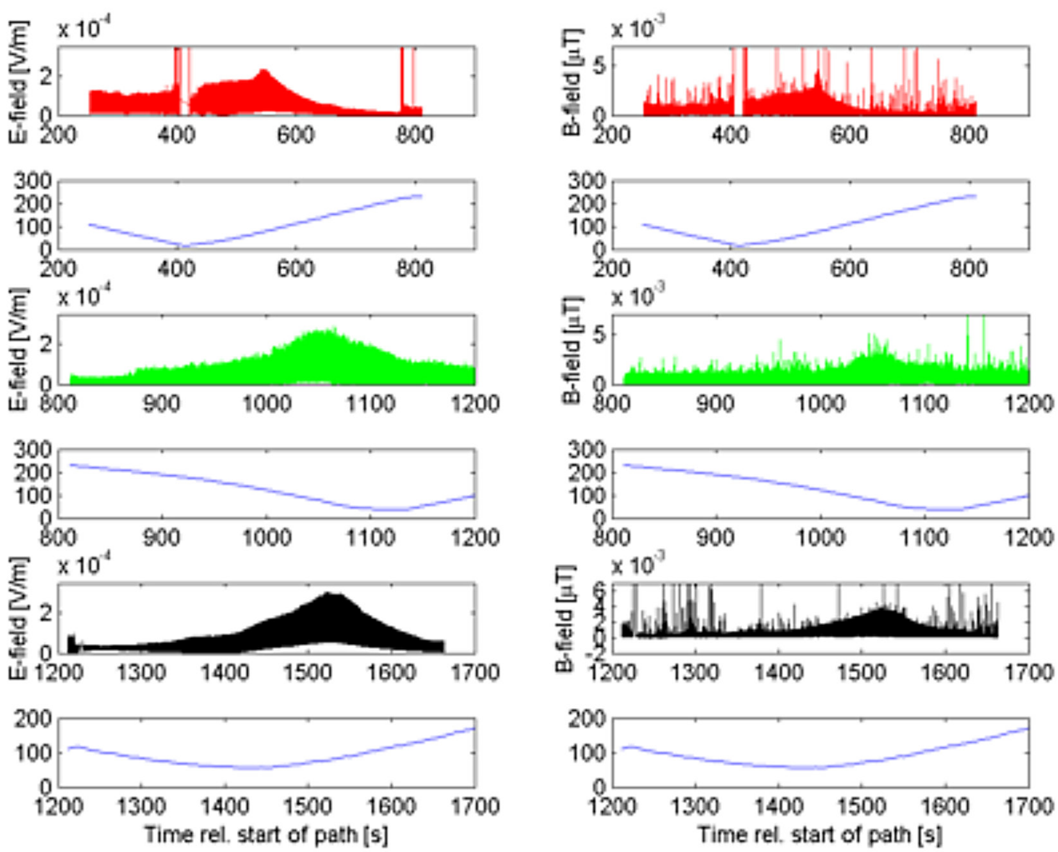

Figure 6.6. The measured electric and magnetic field near a wind turbine at the C-Power wind farm for three different drift paths. The total fields are plotted. The blue graphs show the distance (m) to the turbine as a function of time in seconds (from Thomsen et al. 2015).

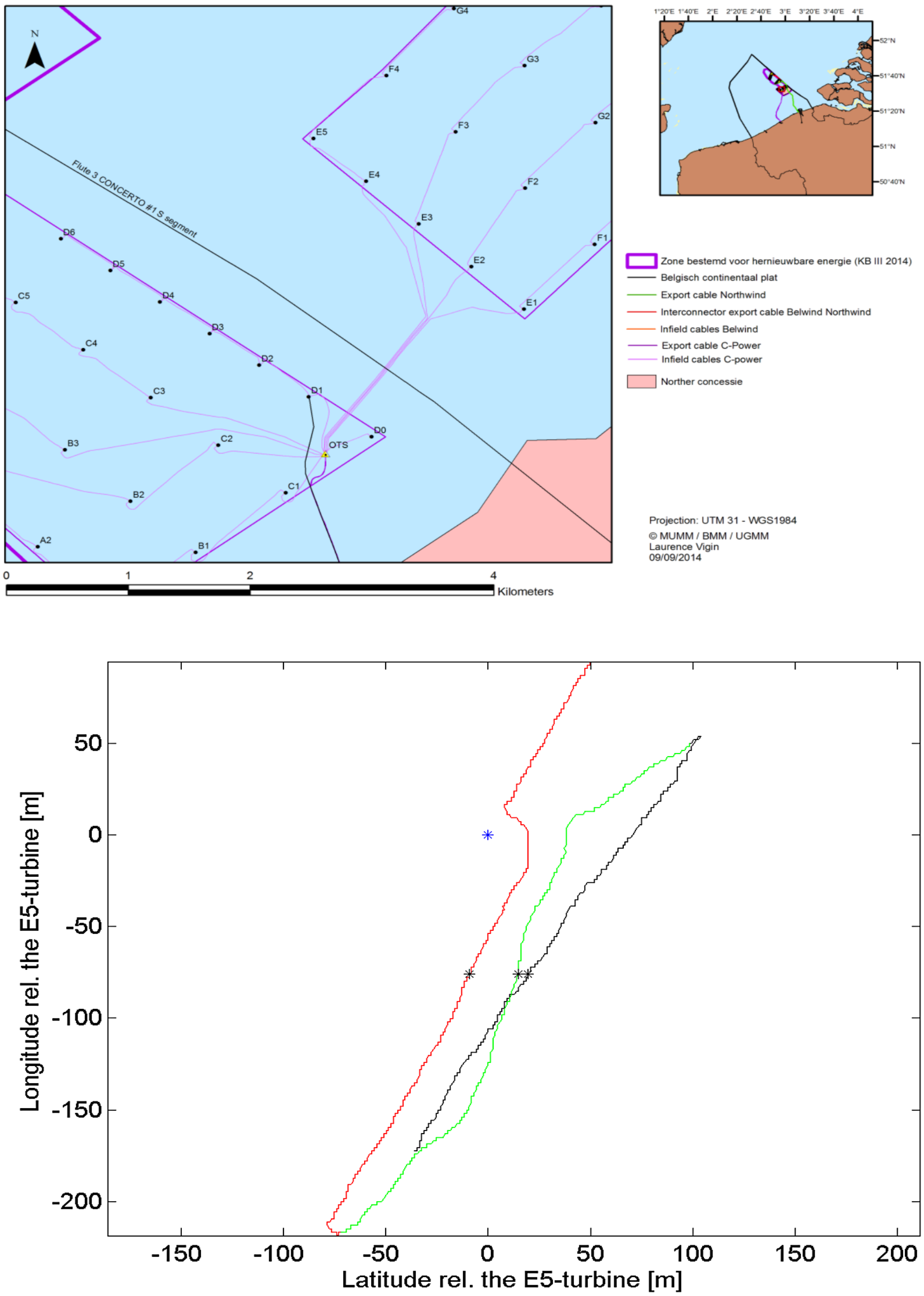

Figure 6.7. Map of the (planned) network of cables at the C-Power wind farm. Turbine E5 is highlighted and the paths of the drifting surveys are shown in the expanded box. Colors of drift surveys match those in Figure 6.6 and the location of the peak in curves shown in Figure 6.6 are indicated by black stars (from Thomsen et al. 2015).

by the 50 Hz component, which is expected in Europe. Current-carrying field densities of 4 μV/m/A and 0.05 nT/A were obtained at a cable-to-sensor distance of about 18 m.

MaRVEN field studies concluded that the EMFs from interarray cables can be detected and they appear to be the dominating source of EMFs inside the MRE device (in this case a wind farm). Any EMF directly associated with the wind turbine is negligible. Both the electric and magnetic fields are observable and the employed methodology is applicable even with the boat engine on.

6.6.2 MEASUREMENT OF FIELDS OF THE NORTHWIND AND C-POWER EXPORT CABLES BY TOWING THE EMF SYSTEM BEHIND THE RIGID INFLATABLE BOAT

The SEMLA was transferred from a mothership to a smaller vessel and then deployed on the seabed to be towed at speeds between 2 and 5 knots. The burial depth of the cable was 1.5 m and the water depth 5.5 m, corrected for the tide. The distance between the sensors and the cable was approximately 6 m.

The electric and the magnetic fields were clearly represented in the recorded time series. The strongest observed electric and magnetic fields were 0.08 mV/m and 0.038 μT, respectively (Figure 6.8), which coincided with the position of the export cables from each of the wind farms (Figure 6.9). The results show that the amplitudes measured were representative and reproducible because the first and fourth peaks and the second and third peaks had the same amplitude (Figures 6.8 and 6.9).

6.7 EMF LEVELS AND SIGNIFICANT BIOLOGICAL EFFECTS

Although research has been limited, anthropogenic sources of EMF from subsea cables have been in the marine environment for over one hundred years, yet no clear EMF levels have been identified to cause impacts. Coarse-scale studies have determined where the behavioral avoidance response to EMF by electrosensitive species is likely to occur—around 1000μV/m and above. But whether exposure to high E-fields is detrimental/harmful is unknown.

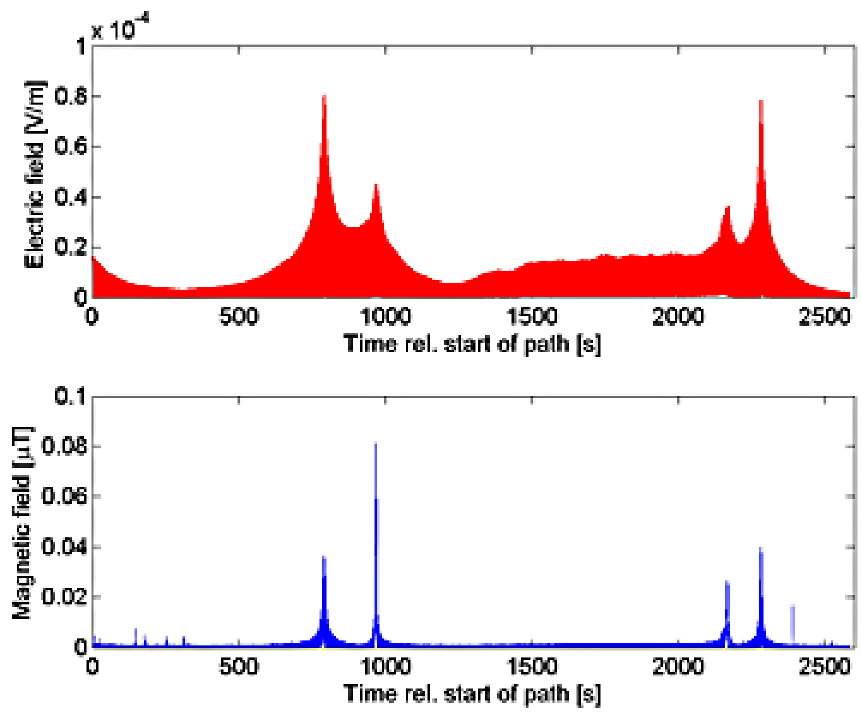

Figure 6.8. Observed EMF by SEMLA when towed over the Northwind and C-Power export cables. The first peak from the left is the Northwind and the second is the C-Power cable. The third peak is the C-Power and the fourth is the Northwind cable. The upper panel shows the electric field and the lower shows the magnetic field (from Thomsen et al. 2015).

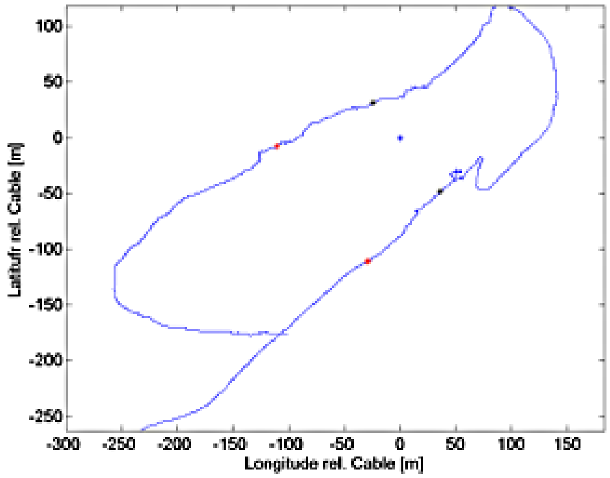

Figure 6.9. The track of the vessel while towing the SEMLA. The blue cross shows the position of the Northwind export cable (from deployment data of the cable). The two black stars show where the strongest fields were obtained for the Northwind export cable and the red stars show strongest fields for the observed position for the C-Power export cable (from Thomsen et al. 2015).

For B-fields, the best evidence to date comes from tracking studies demonstrating a diversion from a migratory path by sensitive species, but this has not been regarded as problematic because the individual eels although attracted to the HVDC cable, resumed their migratory path after tens of minutes (Westerberg and Lagenfelt 2008). Such a diversion would only be regarded as harmful if there was some evidence to show that diverted animals are compromised in terms of wasted energy expended, thereby limiting their ability to reach the location where the migration ends, or the animals become disorientated and unable to reach their target (Gill et al. 2012).

In terms of detriment to early life stage development, the evidence is equivocal. Some larval stages of different taxa (such as crustacea and echinoderms) have been shown to be affected, but there was large variability in the results and other species from the same taxa did not indicate negative outcomes, such as physiological or developmental impairment.

6.8 EMF CUMULATIVE EFFECTS

If there are any consequences for EM-sensitive species of exposure to EMF from MRE devices then they are most likely to be associated with multiple encounters with the EMFs over a short timescale (Gill et al. 2012). For example, if several individuals were diverted from their migratory paths on each encounter with an EMF emitted from a cable, then the accumulated cost in terms of time wasted and energy used in diversion could compromise the animals. This concept parallels the wasted energy argument associated with migratory birds avoiding collision with multiple wind farms (Masden et al. 2009).

Another possible cumulative effect is if animals keep getting attracted to EMF associated with MRE devices because the emission resembles the bioelectric field of potential food sources (Kimber et al. 2014). If the animals continue to respond to every encounter with perceived bioelectric fields then this hunting of inanimate items may result in lack of food gain and also energetic compromise (Gill et al. 2012). Whether this is a likely occurrence or not is unknown. It is also very uncertain whether the animals can learn that there is no benefit in trying to eat a cable or whether they may become habituated to encounter and associate the characteristics of the EMF as non-food (Kimber et al. 2014).
If such learning occurred then the animals would be expected to react upon first encounter but then quickly adapt. Hence the cumulative effect would be minimal. However, there is too much uncertainty related to our lack of understanding of the encounter of EM-sensitive animals with EMFs from MRE devices to allow any definitive conclusion.

6.9 EMF LEVEL OF KNOWLEDGE AND MITIGATION EFFECTS

Awareness of the potential impact of electromagnetic fields on receptive organisms is variable among stakeholders including regulators and the MRE device/electrical power industry. A major reason for this is the lack of scientific knowledge feeding into the understanding. Although the evidence base is growing slowly, we are a long way from providing the required level of certainty/confidence in knowledge about how EMFs affect receptive species and even further from determining if there is any biologically relevant effect that constitutes an impact. The consequence is that no impact threshold values are apparent and this could explain why companies and managers are reluctant to act when there is no clear reason to look at mitigation.

Nevertheless, some mitigation—more by technical design rather than specific mitigation requirements—does exist. The commercial use of the three-conductor cable has the effect of reducing AC EMFs. Furthermore, the use of helically twisted three-conductor cable lowers the emission of EMFs even more (Petterson and Schönborg 1997). The two-conductor cable used in DC power transmission was considered a major step forward from using the seawater as the return conductor; it could be further improved by using co-axial based technology.

A method that has been mistakenly suggested as mitigation is to increase the burial depth of the cables in the seabed. This does not actually reduce the EMF unless the seabed has magnetic properties (which is unlikely in most circumstances). Burial does increase the distance between receptor species and the cable and thus lowers the maximum EMF encountered in the water column. However, this is only of some relevance if it is known that receptor species have some threshold, below which they will behave/respond in some altered manner. For a number of species it actually may mean the EMF is more attractive because it brings the emissions into the range of known attraction. Again, the knowledge base is too patchy and unclear to make any statement about whether burial is of relevance to the question of EMF causing attraction/avoidance in receptive species.

A further factor to consider is that if there is an effect on receptors that requires a reduction in EMF (perhaps necessary with larger electrical current-carrying cables), then there may be a need to consider deeper burial. However, this has serious implications for an engineering solution to bury cables deeper than the current 1 – 3 m. Knowledge of EMF and receptor species response is necessary before any move is made to get engineers to consider the more technically challenging and expensive deeper burial.

6.10 DESKTOP STUDIES – THE APPLICATION OF MODELING

As is evident from earlier sections there are limitations to laboratory and field studies concerned with EMF. These studies can in some case be complemented with mathematical modeling. Models can be a cost-effective method for assessing EMF in a location (see Figure 6.2) and they can be applied to extend measurements to a larger area that would be too costly to cover with multiple measurements. Furthermore, EMFs are often not stable through time, because they are affected by power generation variation and the influence of water movement, which makes multiple measurements with sensors difficult, even if they are available. The modeling can analyze the extent of the EMF emissions and hence the potential spatial footprint of EMFs associated with MRE devices. One main limitation of modeling the EMF is that it still relies on measured fields to assure that the model assumptions are appropriate and the modeled results are valid. The models can be used to investigate design options such as how the field will change when a cable type is altered, and such studies are valuable for lowering the risk as well as the costs of deploying MRE devices.

When considering models it is necessary to remember they will always produce results. This emphasizes the need to have sufficient knowledge of essential parameters; i.e., positions of the cable relative to the EMF sensors and electrical and magnetic properties of the cable material. In addition, most EMF modeling uses drawings of equipment that are perfectly symmetrical, hence any asymmetric geometric displacements or electrical load imbalances are seldom accounted for. An important but unknown parameter is the stability and the electric load balance between the three phases of AC-power transmission. If a large imbalance exists then strong fields will be generated irrespective of the geometrical design of the transmitting power cable. An unknown effect comes from electric transients (i.e., short-term bursts of electricity coming from external or internal variation within the electric power system, circuit, or connections), but MRE devices are designed to handle them by feeding them into the sea. Electric transients are thought to be rare and of low strength. However, this is an assumption and studies are required to determine their relative occurrence and strengths.

6.11
KEY FINDINGS

The review of available knowledge highlighted the following:

- Several taxonomic groups of species are sensitive to electric and magnetic fields. There are large gaps in understanding the response of these animals to the EMFs, so it is not possible to determine whether there is any biologically significant impact of the EMF generated by MRE devices.
- The most likely effects relate to animal attraction to or avoidance of the EMF associated with cables connected to the MRE devices. Hence, further studies of the behavioral responses of different receptor species in relation to different MRE device contexts are required.
- Evidence of the potential effects of EMF on early life stages of receptor species is equivocal; some evidence suggests that some species may be affected whereas others are not. Whether there are any biologically relevant implications for the species population is unknown.
- Due to the lack of understanding and availability of methodologies for measuring EMFs there are no standards or guidelines for the measurement methodology developed to date.
- The most recent evidence of EMFs in the environment emitted by subsea cables comes from the European MaRVEN study, which clearly demonstrated that electric and magnetic fields are emitted by electricity being transported through cables associated with an MRE device (a wind farm) and the separate EMF components (E- and B-fields) can be measured both at the seabed and at tens of meters distance from a cable.
    - The EMF associated with a wind turbine was so low as to be considered negligible.
    - Emitted EMFs were higher for export cables from the offshore wind farms than for the inter-turbine cables. This would be predicted based on the amount of power being transmitted and the lower electrical capacity rating of the cables.
    - The E-fields measured (mV/m) were within the range of known detection by sensitive receptor species. By assuming that the levels measured will propagate as an inverse function of distance, there will be E-fields within the detectable range for sensitive species within the water column and along the seabed for tens of meters away from the axis of the cable.
    - The magnetic fields measured (nT) from the AC cables (50 Hz) were toward the lower end of the detectable range of known sensitive species. Hence, any sensitive species present or moving within the device array or in the shallow waters adjacent to the coast where export cables come to shore are likely to encounter the EMF emitted by the MRE device subsea cables. Whether the species encountering the EMF will respond and that response will be significant from a biological perspective is unknown at this stage.
    - EMF emitted by cables will scale linearly with an increase in cable power and electrical current passing through the cable. It should be noted that the results highlighted here are restricted to AC transmission systems.
- The general void of knowledge and data is presently regarded as a major reason for the uncertainty around EMFs and consequently the passivity of stakeholders to engage with the environmental questions that arise related to EMFs.

Overall, the research to date has demonstrated, to some extent, that different species can detect and respond to EMFs of the type and intensity emitted by subsea cables, but the number of animals studied has been limited and the spatial and temporal scales at which the data have been collected have been restricted. Furthermore, efforts to tag individual animals have not been at a fine enough scale to fully understand the reactions of the individuals to EMF from undersea cables. The inherent variation associated with studying individual animals has led to limitations in the interpretation of data.

Overall, given current understanding, EMFs associated with MRE devices and electrical cables are not known to cause any negative effects on receptor species. This finding is particularly relevant when decisions are being made concerning deployment of single devices and cables or developments with a small-scale environmental footprint. To the contrary, such deployments could be highly beneficial if developers are encouraged and supported to conduct targeted monitoring (sensu Lindeboom et al. 2015) to collect EMF-related data to improve the knowledge base. Such monitoring data could then feed into the considerations of EMF in the future because the lack of evidence to date does not rule out the possibility that negative effects could occur in the future to species not yet considered, and as MRE arrays significantly expand in their individual footprints and in their cumulative number of deployments.

6.12 RECOMMENDATIONS

Further measurements around operating MRE devices should allow this risk to be retired for single devices, while MRE build out in large arrays may require further investigation. Decreasing uncertainty around EMF sources and effects would benefit from additional research.

Research recommendations related to sources, exposure assessment, and dose-response studies are listed below. They are assigned categories to represent recommendations that deal with 1) essential issues that require research investigation, 2) potential monitoring for existing or planned projects, and 3) longer-term research of particular relevance to cumulative assessment.

SOURCES

Requires additional research:

- The findings from the EC MaRVEN studies are from AC transmission systems. The same methodologies need to be used on higher power rated DC transmission systems to determine the EMF characteristics and hence the exposure and potential dose to receptor animals.
- The measurements completed as part of the MaRVEN project were focused on single cables, albeit different cables measured using the same method. What the EMF looks like with multiple cables, particularly those associated with collector turbines/devices or transformer stations, is unknown. For more confident assessments it is necessary to determine if the EMF is greater with multiple cables and if so to what degree (taking into account cable orientation and cable characteristics).

Potential monitoring for existing or planned projects:

- Field-based monitoring studies could be conducted to determine the EMF associated with different types of MRE devices and with different associated hardware in different geographic locations.

Longer-term research for cumulative assessment:

- Sources of EMF are directly related to the electrical topology of the MRE devices. To date, analysis of the electric design of MRE devices to identify the sources and strength of EMF has not been conducted. Filling this gap requires a general analysis of the electrical topology of the MRE devices.

EXPOSURE ASSESSMENT

- Based on the limited existing knowledge related to the EMF emitted by devices and the electrical cable systems and limited understanding of sensitive receptor species and their response(s) to the EMF, it is difficult to make a judgment about the outcome of interactions between marine organisms and MRE device-related EMF. A significant improvement in understanding the fields that cables and devices actually emit is required, and will come from studies linked to the source of EMF (above).

Potential monitoring for existing or planned projects:

- Differences in the emitted EMF-footprint of AC and DC transmissions, which will emit either AC fields or DC fields, respectively, can be predicted. However, from the perspective of the exposed receptor species these fields are very different. DC fields are expected to be dominated by the magnetic component; hence, studies of the emission intensity and extent and its variability through time are needed to understand the likely exposure of species with magnetosensitive abilities that are likely to respond.
- For AC fields there are lower intensity magnetic fields, but electric fields will be induced in the adjacent water and sediment where electrosensitive species may encounter the fields. To fill the gaps in knowledge about what marine animals may be exposed to, measurements are needed at several MRE device installations to establish electromagnetic levels linked to location/depth, device type, number, and extent.

These types of studies are useful to feed into a more effective environmental assessment process. The spatial scale of the EMF needs to be determined, as does the time scale of when a species will likely encounter the fields.

Dose-Response Studies

To determine the effect on marine species of exposure to cable and/or MRE device EMF it is necessary to conduct research within a dose-response scenario that incorporates the likely encounter rate with EMF in the environment (as determined by studies highlighted in the previous section).

Requires additional research:

- The ranges of detection and thresholds of response are poorly understood for the majority of species; further targeted research is required to improve confidence in assessments of species-specific responses to the different intensities of EMF (both AC and DC) associated with MRE device cables.
- By understanding the potential dose response it then becomes possible to assess the risk of animals being affected and whether mitigation measures need to be developed and applied. At present there are few results from relevant dose-response studies. To fill this gap it is suggested that response/effect studies be conducted on marine species, including a focus on the exposure of the most vulnerable life stages to different EMFs (sources, intensities).

Potential monitoring for existing or planned projects:

- To effectively assess the potential impact of EMF on sensitive organisms it is important to consider not just a single EMF from a single cable. There are multiple cables and hence sources of EMF, and the orientation and geometry of the EMF needs to be considered over the whole MRE device footprint (devices and transformers) and the export cables. Ongoing measurements at MRE device sites with different hardware layouts could provide key information to fill this knowledge gap.
- Combining monitoring data from MRE devices with EMF models (e.g., Maxwell finite-element modeling) and dose-response studies with ecological models (e.g., individual based and species population models) is likely to be the most effective and strategic way forward to address the lack of appropriate knowledge. Hence, modeling tools need to be adapted or developed that take the EMF sources and the species-based response into account.

Longer-term research for cumulative assessment:

- To determine whether any biologically significant impact (as opposed to a response) occurs when receptive animals are exposed to EMF, several parallel studies are needed. These studies should look at vulnerable life history periods and the likelihood of encounter with EMF over the scale of typical MRE devices, and also cumulatively when considering adjacent MRE devices (as exemplified by offshore wind farm plans in marine planning zones, such as those under consideration for the United States East Coast). From these studies, the outputs need to be framed with an analysis of emergent properties associated with impact at the biologically relevant unit of the species population.

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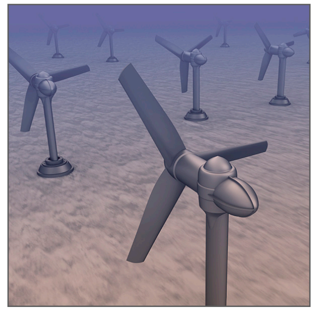

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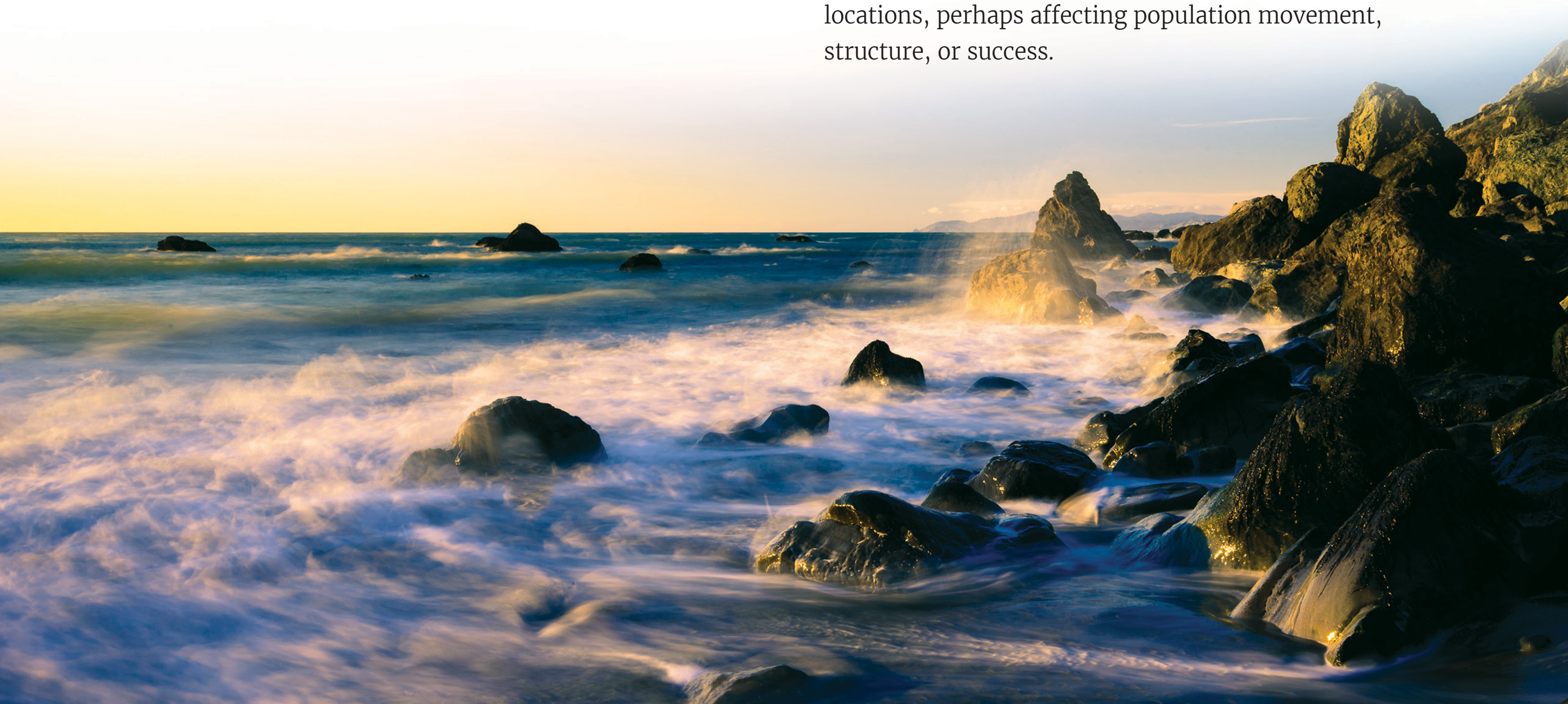
Changes in Habitats Caused by Marine Renewable Energy Devices: Benthic Habitats and Reefing Patterns

The installation of MRE devices alters marine habitats through mechanisms that induce physical change. These changes in habitat have the potential to alter or eliminate species occurrence at a localized scale, provide opportunities for colonization by new species, alter patterns of species succession, and induce behavioral responses in marine organisms.

All MRE devices must be attached to the sea bottom in some manner, either with gravity foundations, piled into the seafloor, or by one of several anchoring solutions. The placement on the seafloor, as well as movement of anchor lines, cables, and mechanical moving parts, can all affect the surrounding rocky or soft-bottom seabed and the benthic organisms these habitats support (Figure 7.1). Similarly, the presence of MRE devices on the seafloor or suspended in the water column may attract fish and benthic organisms, causing them to change their behavior and settling locations, perhaps affecting population movement, structure, or success.



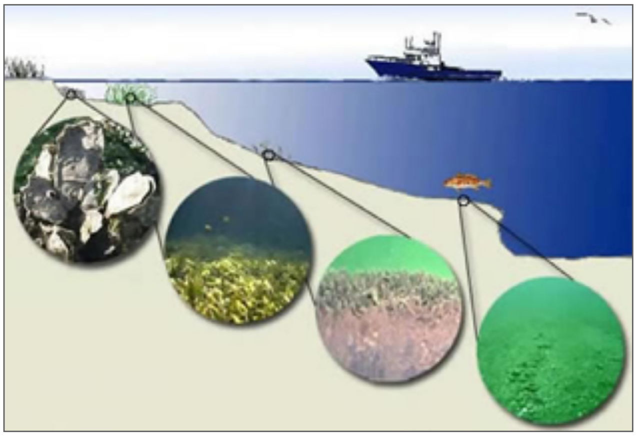


Figure 7.1. Coastal benthic habitats and organisms; oyster beds, seagrass, amphipod tubes, sandflats. (Source: NOAA Office for Coastal Management)

7.1 GOAL AND OBJECTIVES

The goal of this chapter is to summarize the state of understanding of changes to habitats from MRE devices by examining potential interactions of benthic organisms with MRE devices as well as reefing patterns of marine animals around tidal and wave energy devices.

Specific objectives include the following:

- Identify MRE projects that have pre- and post-installation data that address potential changes in benthic habitats and communities, and patterns of reefing organisms.
- Examine research and monitoring data for surrogate structures that may inform alterations in benthic communities and habitats, as they apply to MRE projects.
- Examine recent summaries of surrogate structures for reefing patterns and effects that mimic MRE devices.
- Determine key data gaps and research recommendations for determining patterns and the importance of changes in benthic habitats, organisms, and reefing patterns around MRE devices.

7.2 APPROACH

The study of marine benthic ecology, including changes in benthic community structure, is a well-established science. Similarly, many scientific papers and studies have focused on the patterns of reefing and potential implications on fish and other communities. This chapter focuses on the particular effects that MRE devices may have on benthic organisms through changes to habitat as well as reefing effects. As such, only small portions of the scientific literature are presented, and potential effects are discussed in the context of wave and tidal devices. A few key surrogates are also discussed because they may provide insight into what can be expected as MRE devices, particularly arrays, are developed. Although there are no indications that MRE devices will affect marine animals or habitats in a substantially different manner than other structures placed in the ocean, regulators and stakeholders may continue to have concerns. As more MRE devices are deployed, similarities between effects of MRE devices and other artificial structures, as well as potential differences, will become clear.

7.3 SOURCES OF INFORMATION

Information for this section of the report was derived from scientific peer-reviewed publications and augmented by reports from marine energy deployments that are documented in the Annex IV metadata forms (housed on *Tethys*). Because few marine energy deployments have been in the water long enough to detect significant changes in benthic habitats and communities, or to support many studies of reefing around them, surrogate structures have also been used to make broad inferences about benthic interactions with underwater devices (Henkel et al. 2014; Krone et al. 2013a; Krone et al. 2013b; Mineur et al. 2012), including studies at offshore wind farms. Devices such as coastal defense structures and oil rig platforms were deemed less relevant for this review because they typically occur in habitats and at water depths that do not offer adequate comparisons for the goals and objectives of this review. A recent report by H.T. Harvey and Associates (2015) was used to provide a regional assessment of reefing potential at wave and tidal devices for marine fishes along the west coast of the United States and coastal Hawaii.

7.4
EFFECTS OF MRE DEVICES ON BENTHIC MARINE ORGANISMS

Interactions with benthic resources and MRE devices can occur at all phases of a wave or tidal project—pre-construction/siting, construction, operation, and decommissioning. The scope and the potential effects of these interactions on benthic resources is likely to vary because of physical factors (biogeographic region, site location, water depth, tidal current velocity or wave height, and other factors), as well as the biological features of the community, including the number of benthic species, total numbers of organisms, and the spatial distribution over the seafloor. The specific design of marine energy farms will also determine their potential effects, including the technology of the machines, the scale of the turbines, foundations, WECs, anchors, mooring lines, and export cables. Adverse effects on the benthos that might be expected include loss of numbers and species of benthic organisms, degradation of habitat, and creation of pathways for invasive species to become established. Questions also arise concerning the potential cumulative ecological impacts from many MRE devices deployed in marine environments (Witt et al. 2012). Similarly, the likelihood and extent of significant reefing occurring around a marine energy site will be affected by the number of devices and their placement in the water column, as well as the species of fish and mobile invertebrates (such as crab, shrimp, squid, etc.) prevalent in an area (Langhamer 2012).

Despite the potential for adverse effects, the installation of MRE devices may also provide opportunities for creating and enhancing habitats that favor benthic species, increase the number of fish in an area as they reef around the devices, and create de facto marine protected areas. Opportunities for development of compatible industries like aquaculture may also be provided (Inger et al. 2009; Langhamer 2012; Witt et al. 2012). Research on the interactions between benthic organisms and a tidal energy device at the EMEC indicated greater species diversity at the device site compared to a control site, and a pattern of increasing species richness over time (Broadhurst and Orme 2014). Similarly, video taken around a tidal device at EMEC shows an abundance of fish reefing and feeding around the device, particularly at slack tide (Broadhurst et al. 2014). Off the west coast of Sweden, Langhamer and Wilhelmsson (2009) determined that wave energy foundations added structural complexity to the seabed, leading to higher abundances of benthic organisms than found nearby on the seabed.

7.4.1
SEAGEN TIDAL TURBINE

The SeaGen tidal turbine, installed in Strangford Lough in April 2008, consists of a four-footed foundation spanning a 18 m by 12 m area. Each corner of the foundation is supported by a pin pile, which raises the base of the structure approximately 2 m above the seabed. The four-footed foundation supports a 3 m diameter pile that comprises a cross beam with a 16 m diameter rotor affixed to each end (Keenan et al. 2011).

In water depths ranging from 25 to 27 m, sampling stations were established in-line at varying distances (20 m, 150 m, and 300 m) from the turbines, as well as at a nearby reference site (located 50 m from the turbine). Data were derived from diver-collected video at the four sample stations. Pre-installation data were collected in March 2008 and subsequent post-installation surveys were conducting during July 2008, March, and July 2009, and April 2010. During 2008 and 2009, the turbine was operating at a low level (Keenan et al. 2011).

Keenan et al. (2011) report that benthic communities were different during each subsequent survey; i.e., there were detectable changes through time. Changes in benthic communities were attributed to a combination of temporal variability and natural processes associated with species interactions (e.g., competition and succession). Overall, changes in community composition were similar across all sampling stations, including the reference station. Keenan et al. (2011) report the monitoring program was sufficient to detect community level changes and conclude there were no negative effects on benthic communities associated with installation of the tidal turbine.

The structural attributes of the SeaGen tidal turbine, the underwater cylindrical structures, and the shoes affixed to the seabed were noted to provide habitat for benthic biota. The types of organisms found to colonize and associate with the cylindrical structures include mussels, barnacles, hydroids, bryozoans, limpets, and brittlestars. Benthic organisms found to associate with the shoes include barnacles, hydroids, and crabs. Video surveys and subsequent analyses indicate colonization of 37.6 m^2 at the SeaGen structure has exceeded the 36.3 m^2 of benthic habitat that was replaced by the installation footprint. While not identified during pre-installation surveys, the occurrence of mussel species following installation of the SeaGen turbine was viewed as beneficial because these species are thought to contribute as a food source for other organisms (Keenan et al. 2011).

7.5
POTENTIAL CHANGES TO BENTHIC HABITATS

Installation of MRE devices may affect environmental conditions that define and sustain benthic habitats, including such physical properties such as sedimentation patterns, hydrodynamics, and seabed conditions (De Backer et al. 2014). The spectrum of potential changes caused by tidal energy devices could include positive attributes (e.g., habitat creation) as well as negative ones (e.g., smothering of benthic fauna) (Frid et al. 2012). Similarly, the presence and operation of WECs could affect benthic habitats. Modeling of the effects of mooring lines from an oscillating water column WEC sweeping across the seafloor showed a direct relationship between wave height and the affected area of benthic habitat (Krivtsov and Linfoot 2012); more than 60 m^2 of benthic habitat at wave heights of 6 m were affected. At offshore wind farms, the interaction between turbine foundations and local hydrodynamics affect sediment characteristics by reducing flow and preventing the re-suspension of finer sediments and sand around a device (Coates et al. 2014). In addition, alteration of the natural hydrodynamics near turbine foundations can result in bottom scour.

7.6
POTENTIAL EFFECTS ON BENTHIC ORGANISMS

The presence of an organism in a particular location is governed by the life history of the species. New habitats may be created by introducing marine energy infrastructure, providing support for species in areas where they are not presently found (Adams et al. 2014), and providing connectivity among adjacent habitats that may allow species to move across broad expanses in a way that was previously impossible (Miller et al. 2013). These new habitats may help some species succeed, but there is also potential for invasive (non-native) species to gain footholds and move across habitats because MRE devices may act as attractants or stepping stones (Bergstrom et al. 2014; Miller et al. 2013; Mineur et al. 2012; Witt et al. 2012). While there have been reports of non-native species colonizing underwater structures associated with offshore wind devices (c.f. Langhamer 2012), there are few data that help scientists understand the likely mechanisms for invasions or predict the ecological implications that may result (Mineur et al. 2012). In high-energy environments where renewable marine energy development is likely, invasive organisms best suited to become established are those that can endure strong hydrodynamic conditions (Mineur et al. 2012), such as those that typically survive on vessel hulls by creating strong encrusting shells or coverings, or that have strong but flexible bodies.

A considerable amount of scientific literature supports the creation of new benthic habitat on and around MRE devices, but it is more difficult to determine how this habitat benefits or harms native species. Benthic macrofauna (organisms larger than 1 mm) at the Lysekil WEC project off the west coast of Sweden were found to have higher biomass, density, species richness, and species diversity than at a nearby reference location (Langhamer 2010). However, the very large spatial and temporal variability of the benthic macrofauna made it impossible to statistically determine differences between the locations. In an investigation of the short-term (i.e., <12 months) effects on benthic resources at the Egmond aan Zee offshore wind farm off the Netherlands coast in the North Sea, no differences were seen in the benthic macrofauna between the offshore wind farm and the reference locations (Lindeboom et al. 2011). Using a BACI analysis, more juvenile and adult sandeels were observed at the Horns Rev I offshore wind farm in the North Sea off Denmark the first year after construction than previously noted, although the variability was high (van Deurs et al. 2012). When the researchers revisited the site seven years after construction, no effect, relative to pre-construction, was apparent on the sandeels and their habitats (van Deurs et al. 2012).

Deployment of MRE devices may alter benthic communities; most evidence to date comes from offshore wind turbine foundations. In a small-scale study at the Thorntonbank wind farm off the Belgian coast, measurements of organic matter close to a wind foundation were higher than in the background water. This increase appears to support colonies living on the surface of the seabed (epifaunal organisms), as well as large groups of sand worms (*Lanice conchilega*), which are known to which are known as 'ecosystem engineers' (Coates et al. 2014). The vertical structure of a wind turbine foundation allows for colonizing species such as blue mussels (*Mytilus edulis*) to become established, which leads to the creation of other habitats such as mussel shells. These new habitats thus encourage colonization by other benthic organisms, increased levels of organic matter, and filtration of large amounts of seawater (Krone et al. 2013b). Device developers are concerned that biofouling of MRE devices may cause some risk to their devices; at the same time, excessive numbers of biofouling organisms on tidal or wave devices may consume oxygen and create large amounts of fecal deposits that could result in hypoxic or anoxic conditions on the seabed below. Biomass sluffing combined with bacterial decomposition has been shown to lead to lower than background oxygen close to a wind farm, but these conditions were not detected across a larger area (Janssen et al. 2015).

7.7 SCALE AND GRADIENTS OF BENTHIC INTERACTIONS WITH MRE DEVICES

The benthic communities living on the surface of underwater devices (also known as epifauna) are likely to be influenced across a range of spatial and temporal scales, as well as by oceanographic processes such as currents, sedimentation patterns, and patterns of plants and animals (Miller et al. 2013). For example, Krone et al. (2013b) found that shallow underwater foundations close to shore attract denser colonies of blue mussels (*M. edulis*). A nearshore to offshore gradient of bivalves was also noted by Lindeboom et al. (2011) in a study at an offshore wind farm where sites with higher densities occurred at nearshore locations. Patterns of benthic communities measured at offshore wind turbine foundations differ with distance from the wind turbines because of changes in water flow and organic input. Other contributing factors may include sluffing of bivalve shells from the turbine foundations (Wilhelmsson and Malm 2008), deposition of fecal pellets and detritus from benthic communities living on foundations, and regional coastal currents (Maar et al. 2009).

For single MRE devices, examining the portion of the water column covered by the foundation may help determine the effects on benthic communities and the extent to which organisms will reef. For example, offshore wind foundations and WECs may occupy the entire water column, while tidal devices are generally restricted to deeper depths (Adams et al. 2014). The extent to which benthic organisms colonize a single MRE device may not be indicative of what we can expect around multiple devices in an array (Coates et al. 2014), particularly if we look at colonization of devices over large spatial scales (De Backer et al. 2014).

Benthic organisms will begin to colonize underwater structures as soon as the structures are deployed. Evidence from early colonization during construction of offshore wind farm foundations does not appear to have an effect on the nearby environment, but it is not clear what the patterns and effects of such colonization may be over the long term (Lindeboom et al. 2011). Under natural ocean conditions, benthic communities undergo succession with changes in the dominant species and groups as the communities reach a mature stable state. This pattern of succession must be taken into account when monitoring species composition and abundance of benthic communities around MRE devices in order to determine whether observed changes are due to natural causes or associated with the presence of the MRE devices. There is no clear evidence of when successional equilibrium may be reached in benthic communities (De Backer et al. 2014; Lindeboom et al. 2015); this endpoint likely varies with environmental conditions and a specific MRE device.

7.8
REEFING BY MARINE ORGANISMS AT MRE DEVICES

The attraction of organisms to objects such as MRE devices that are placed in the marine environment, either on the seabed or in the water column, is referred to as reefing. In some circumstances, this attraction of organisms is viewed as a positive outcome resulting from MRE devices. Because the effects of MRE devices on animals is dependent on their presence in the region of the device (ABPmer 2010; Romero-Gomez and Richmond 2014; Amaral et al. 2015) it is worth considering the added benefit and/or risk associated with animal presence; it might be related to the attraction of certain fishes to a new structure in their environment. The attraction of fish to man-made structures has been used for enhancement of fishing opportunities (Brock 1985; Dempster and Taquet 2004) or diving experiences (Langhamer 2012). FADs are purposely placed to attract large numbers of pelagic fish and decrease human search time for fish. Similar results are found for species attraction to other offshore man-made structures: vessels (Røstad et al. 2006); structures associated with marinas and pontoons in urban areas (Clynick et al. 2008); net cages used for aquaculture (Oakes and Pondella 2009); sunken vessels (Arena et al. 2007); and underwater depuration systems (Cattaneo-Vietti et al. 2003). Organisms reef to shelter from predators or harsh environmental conditions, as well as when they are attracted to food that may be growing on or associated with MRE devices and underwater structures (Langhamer 2012). While reefing may provide benefit to fish and some mobile invertebrates such as crab and squid, it may also attract invasive (non-native) species (Mineur et al. 2012).

The potential for fish to be attracted to MRE devices has been hypothesized (Gill 2005; Čada et al. 2007; Boehlert and Gill 2010), and there are now more specific indications that attraction to devices will occur by predatory fish species (Broadhurst et al. 2014) with an associated increase in local biodiversity near the device (Broadhurst and Orme 2014). Increased biodiversity of fish and predators was observed near a tidal device site at EMEC, compared to a control site, which may indicate the structures create reefing opportunities (Broadhurst and Orme 2014). As a result of variable temporal ecological patterns Broadhurst and Orme (2014) identified the need for longer-term studies but caution the stage of the industry makes that difficult. At the Lysekil wave test park on the west coast of Sweden, more fish were seen near the wave device foundations than at a control site, although the change was not statistically significant (Figure 7.2; Langhamer et al. 2009).

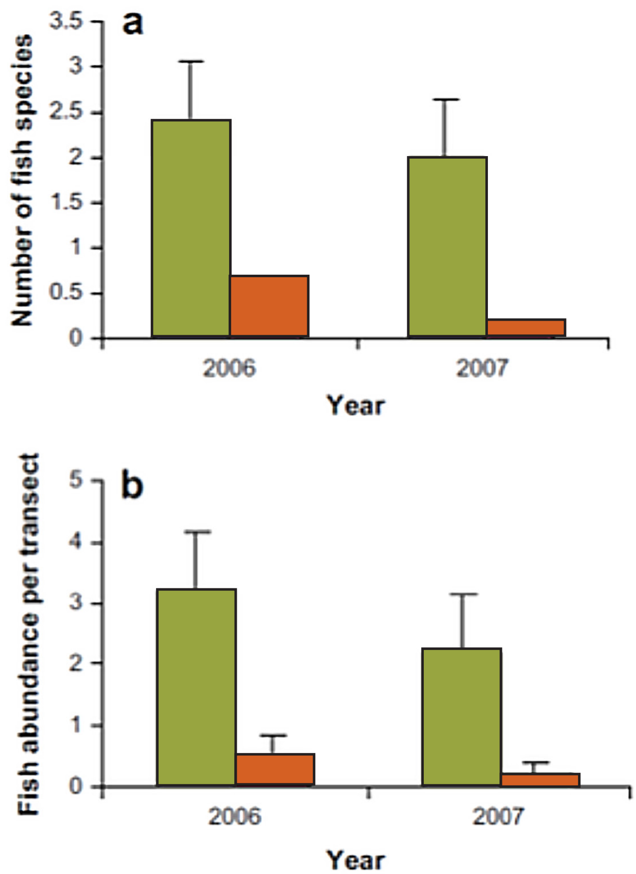


Figure 7.2. Number of species (a) and abundance of fish (b) observed at wave power foundations (blue) at the Lysekil Wave Test Park and within control areas (purple). (From Langhamer et al. 2009)

Underwater structures associated with wind and wave devices have been reported to attract marine animals (Page et al. 1999; Peterson and Malm 2006; Vaselli et al. 2008; Wilhelmsson and Malm 2008; Langhamer et al. 2009; Langhamer and Wilhelmsson 2009; Krone et al. 2013a; Munari 2013; Wehkamp and Fischer 2013), some specifying attraction to the piles of offshore wind farms (Wilhelmsson et al. 2006; Linley et al. 2007) and some reporting changes to local abundance as well as diversity similar to daily and seasonal changes in fish assemblages associated with oil platform structures that vary according to the size of the platform studied (Soldal et al. 2002).

The attraction of fish to areas of hard substrate located over soft-bottom habitats was demonstrated at shipwreck sites in the German Bight using a structure considered to be analogous to a wind turbine foundation (Krone et al. 2013a). These structures provided habitat for organisms that would otherwise be limited to natural rocky habitats (Krone et al. 2013a). The extent to which fish and other organisms are likely to reef around a structure is defined by the size and available surface area of the structure (Krone et al. 2013b), as well as the lure of organisms growing vertically on structures that may create new habitats both on the structure within the water column and below on the seabed (Krone et al. 2013a). An extensive review of studies of reefing and FADs around surrogate structures has been prepared (H.T. Harvey and Associates 2015) as a means of understanding potential reefing around wave and tidal devices (see boxed information on next page).

In areas with high flow rates such as tidal rapids, pelagic fish will be unlikely to aggregate for long periods (ABPmer 2010). The influence of small pelagic fish gathering in an area could influence the presence of larger, predatory fish and should be considered when assessing risk, even though fish may use areas of lower turbulence regions around devices as shelter, such areas may not be extensive enough for flow refuge.

7.9 DISCUSSION AND IDENTIFICATION OF DATA GAPS

Scientific peer-reviewed literature on the interactions of benthic organisms and habitats with offshore renewable energy devices is dominated by studies examining the potential effects of offshore wind turbine foundations. While surrogate structures provide some insight into potential interactions, field data are needed to understand the effects, scale, and variability of benthic and reefing responses to the presence and operation of MRE devices. The only field study examining benthic communities at a deployed tidal device found that there was increased diversity and numbers of benthic organisms over time, in comparison to a control site (Broadhurst and Orme 2014). WEC foundations appear to offer structural habitat features for benthic organisms, and also attract more organisms than nearby bare seabed (Langhamer et al. 2009). Spatial context (i.e., siting and project footprint) plays an important role in interpreting potential changes to benthic habitat and reefing of fish at MRC devices. Extensive homogeneous habitats at offshore locations will likely elicit a different response than enclosed nearshore waterbodies.

Few data are available to definitively describe the relationship of MRE devices and changes in benthic communities, even if control sites are included in studies; even fewer data inform the natural variability of benthic communities in localized areas such that changes due to the presence and operation of MRE devices might be pinpointed (Pearce et al. 2014). While BACI studies may help frame the questions around the potential effects of deploying MRE devices, the natural variability can confound the interpretation of these studies (Lindeboom et al. 2015). As discussed in Chapter 5 of this report, modeling studies can provide insight into the natural processes that may be affected by MRE devices, such as sedimentation patterns and hydrodynamics, which can in turn affect benthic habitats and communities. However, these models have generally not been validated with field data and cannot adequately predict ecological changes or clarify the spatial and temporal variability of benthic responses in localized areas (Miller et al. 2013).

Offshore wind farms appear to act as reasonable surrogates for changes in benthic communities, reefing populations, and species diversity at wave and tidal devices. No offshore wind farm studies to date have shown major deleterious effects on benthic communities or reefing fish; however, the time scales over which these devices have been monitored do not enable the examination of whether benthic communities have reached equilibrium or whether reefing communities are in balance with nearby populations (De Backer et al. 2014; Lindeboom et al. 2015; Lindeboom et al. 2011). Increases in the number of species and total number of benthic organisms and fish have been noted in the vicinity of underwater structures, but it is unclear whether these aggregations are robust populations or whether they represent movement away from other nearby communities, thereby creating a zero sum game of organisms (Miller et al. 2013).

While there are few surrogates for wave and tidal devices, none mimic arrays (Miller et al. 2013); although groups of navigation buoys may mimic small wave arrays, and there is virtually nothing known about

REEFING AND FADS – A REGIONAL REVIEW

Summary of H.T. Harvey and Associates (2015) Report

Using surrogate structures, H.T. Harvey and Associates (2015) evaluated the potential ecological interactions with wave and tidal devices in waters of the U.S. West Coast and Hawaii. This effort focused on determining how these devices may function as artificial reefs or FADs. The surrogate devices reviewed included artificial and natural reefs, oil and gas platforms, kelp beds, marine debris, FADs used for enhanced fishing opportunities, aquaculture net pens, and overwater structures such as piers and docks.

Reefing opportunities at wave and tidal devices stem from attributes such as the addition of hardened substrates, creation of vertical relief, and the addition of habitat complexity. The structures themselves may also attract and aggregate fish. As defined in this report, the two functions of reefing and FADs are distinguished by their locations within the water column, as well as the response of the fish. Artificial reefs provide habitat for fish and other marine organisms living near the seabed. FADs act as an attractant for fish at surface and midwater locations, primarily in open water. Benefits of both functions include enhancement of production, dispersal of organisms, creation of refuge, and improvements in prey resources. Other potential benefits from reefing and FADs include connecting habitats to allow fish to move over long distances, creation of de facto marine reserves, and increased recruitment and settlement of pelagic larvae. In terms of potential negative effects, the attraction of fish to a device may increase opportunities for predators, which is of concern mainly for fish populations that are already depleted and may have special legal protection.

Many of the surrogate structures evaluated resemble wave and tidal devices near the seabed, as well as at midwater and surface-water locations. Fish assemblages across each of the subregions were similar at various surrogate structures; these similarities make comparisons between surrogate devices and MRE devices reasonable. MRE device anchors and foundations are likely to attract fish and cause them to reef. There is less conclusive information about whether fish will be attracted to portions of wave and tidal devices in the water column, because fewer surrogate data are available for these habitats throughout the U.S. West Coast and Hawaiian Islands.

The number of MRE devices deployed will determine the extent of reefing and FADs; larger arrays will likely have a greater effect on local fish populations. Arrays may also create opportunities for connecting artificial habitats and may result in high densities of fish. However, the lack of habitat complexity associated with device structures may minimize some of these benefits. There are concerns that large aggregates of fish around devices may expose them to higher predation, but there is no direct evidence of this.

potential cumulative effects that might arise (Witt et al. 2012). There is reason to believe that the extent of benthic and reefing impacts on marine populations will depend on the size of arrays and seabed involved, but that most effects will be reversible when devices are removed or decommissioned (Frid et al. 2012). It is unlikely that the deployment and operation of MRE devices will have effects as large or widespread as other marine activities such as bottom fish trawling (Witt et al. 2012).

7.10 SIGNIFICANT GAPS IN DATA

Few studies have systematically quantified change in benthic habitats and communities at wave and tidal energy sites. While limited, the current research of MRE interactions with habitats (primarily based from offshore wind devices) suggests structural changes to habitats may offer added opportunities for colonization and reefing. There is not enough research specific to tidal and wave energy devices to adequately evaluate the magnitude of potential risk. These risks are constrained by device specific parameters as well as interactions with environmental conditions, geographic locations, and species-specific responses.

Regardless of the level of uncertainty of risk, considerations for adverse impacts include loss and/or degradation of habitat, alterations of natural disturbance regimes, loss of species, and increased opportunities for establishing invasive species. Relatively little is known about long-term effects in habitat change from MRE devices and the trajectory for recovery if adverse conditions result from installation of devices. Reefing activity around MRE devices has been given scant research attention. Information gained from benthic and reefing studies at offshore wind devices provides a number of valuable lessons and can help address data gaps, including questions of spatial and temporal variability and cumulative effects of MRE arrays. Key data gaps include the following:

- There is an overall lack of studies relating the response of benthic communities and reefing activities to the presence and operation of wave and tidal devices. This literature review relied largely on surrogate devices, and while changes to benthic communities and habitats from wave and tidal devices is not expected to differ from other marine industries, the lack of device specific quantitative information makes it challenging to minimize this uncertainty.
- Information about the potential effects on benthic communities and effects of reefing around MRE devices is needed from multiple biogeographic areas to ensure that responses found in the few existing studies are applicable elsewhere. Tidal and wave test sites might provide excellent locations for these studies.
- Studies of benthic responses and reefing effects are often based on the presence of a single structure. Scaling of responses in space and time are needed to ensure that potential responses are properly contextualized. Potential benthic and reefing effects from the cumulative impacts of arrays or multiple wave and tidal sites located within close proximity to one another have not been addressed.
- Eventually, the potential effects of benthic and reefing changes from MRE devices must be put into a framework of ecosystem changes, including the potential for cascading effects in the marine food web caused by introducing or eliminating species or numbers of organisms from the natural ocean spaces.
- While models of benthic community change and reefing effects have been used to predict potential changes around MRE devices, model validation is generally lacking. Field data are needed to ensure that the modeling results are realistic and can be used over a range of spatial and temporal scales associated with commercial farm development.

7.11 RECOMMENDATIONS

Although data collected at any MRE project will be specific to the project needs, each contribution adds to the collective level of understanding of benthic effects and reefing outcomes. It is essential that research and monitoring efforts be adequately controlled and results disseminated to ensure that the MRE industry is able to apply the knowledge and make informed decisions moving forward.

Research needs to be conducted to

- Discern source populations of reefing communities that associate with underwater structures such as MRE devices; i.e., determining whether populations have grown in response to the structure or have simply migrated from other nearby locations.
- Understand the cumulative effects of multiple devices on community composition and distribution.

- Determine whether MRE devices create novel opportunities for invasions by non-native species.
- Determine whether colonizing species alter ecosystem processes through increased inputs of organic matter.
- Determine the influence of device type on the extent of habitat change and reefing patterns for organisms.
- Evaluate patterns of succession by marine organisms at wave and tidal devices and determine the spatial and temporal extent of successional equilibrium in benthic communities.

Monitoring efforts should be conducted to

- Assess the impacts at wave and tidal device locations. Ideally, these monitoring efforts would include a BACI or similar design to evaluate benthic communities in response to installation and operation of wave and tidal devices.
- Characterize the extent of reefing by marine organisms at wave and tidal devices.

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Marine Spatial Planning and Marine Renewable Energy

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Marine spatial planning (MSP) is a comparatively recent approach to planning and managing sea uses and users in a way that helps achieve sustainable development of marine areas. The rationale for MSP is to provide a stable and transparent planning system for maritime activities and users within agreed-upon environmental limits to ensure marine ecosystems and their biodiversity remain healthy.

MSP works across multiple sectors, within a specified geographic context, to facilitate decision-making about the use of resources, development, conservation, and the management of activities in the marine environment both now and in the future. To be effective, MSP should be integrated across sectors, ecosystem-based, participatory, strategic, adaptive, and tailored to suit the needs of a predetermined marine area. Currently, marine activities tend to be managed on a sector by sector basis, thereby limiting the consideration that can be given to other marine activities likely to occur in the same space, as well as the effects of that activity on the receiving environment. Processes such as environmental assessments address the impacts of an activity on the environment before a development or activity occurs, but this can be limited to a specific site and cumulative impacts remain a challenge for those processes. Failure to take a more holistic approach to planning can result in conflicts between different marine users and activities and also conflicts with the physical environment (Figure 8.1). Conflicts usually result in "reactive" management rather than more proactive management where agreed-upon desired outcomes can be facilitated.

Figure 8.1. Representation of different potential marine users and conflicts of interest (Sutherland 2005).

Many definitions of MSP exist and the terms "maritime" and "marine" appear to be used synonymously in the context of spatial planning as it relates to sea spaces. General parlance would suggest that "marine" refers to the physical ocean space and its living resources whereas "maritime" refers more to industry based on the sea and is used to describe ships, shipping, and their associated activities. In the EU, the key instrument for protection of biodiversity in sea spaces in the *Marine* Strategy Framework Directive. The main EU policy on sea-based activities and their coordinated management is the Integrated *Maritime* Policy. In the EU, the term "Maritime" Spatial Planning is preferred because it is viewed as capturing the holistic and cross-sectoral features of the process (COM[2008] 791 final), and it is this term that is used in the recently adopted Directive on the topic. Hildebrand and Schröder-Hinrichs (2014) state that in every other location in the world where spatial planning in the ocean is being undertaken, the process is referred to as marine spatial planning. The United Nations Educational, Scientific and Cultural Organization defines MSP as "a public process of analysing and allocating the spatial and temporal distribution of human activities in marine areas to achieve ecological, economic, and social objectives that are usually specified through a political process" (UNESCO 2009). The European Commission describes MSP as planning when and where human activities take place at sea so as to ensure that these activities are as efficient and sustainable as possible. Regardless of the term or definition used, the advantages of MSP are widely cited as having social, economic, and environmental benefits.

As a process that has the potential to influence activities in marine spaces now and in future, the implementation of MSP is of direct relevance to the MRE sector. This chapter explores whether and how MSP is being carried out in countries that participate in the work conducted under Annex IV[4] of the International Energy Agency's Implementing Agreement on Ocean Energy (IEA-OES). The content of this chapter is derived from a questionnaire completed by all Annex IV participant countries and, where appropriate, supplemented by relevant external documentary sources. Currently, there are 13 participant countries.[5] The survey included questions about whether the needs of the MRE sector had been incorporated into MSP and how this was achieved, how scientific information is used, how cumulative impacts are addressed, how conflicts are managed, how other stakeholders are involved, and if there are any possible limitations to implementing MSP now or as the sector becomes more visible. The full version of the questionnaire is included in Appendix A. Each topic is covered thematically in the following sections.

8.1 APPROACHES TO MARINE SPATIAL PLANNING IN ANNEX IV PARTICIPANT COUNTRIES

Participant country representatives were asked if formal MSP processes exist in their country. Of the 11 countries that responded 4 have formal MSP processes in place, 3 do not, and 4 do not have MSP in place but do have coastal management plans in place, which can include marine and coastal uses such as shipping, fisheries, and conservation. All countries are at a different stage of implementing MSP and this can take many different forms. MSP can have a formal legal basis as is the case in many European countries (Belgium, Germany, UK), or it can be more strategic and advisory in nature where its implementation is reliant on existing authorities. In the European Union, MSP is now a legal requirement since the European Parliament and the Council adopted a Directive establishing a common framework for MSP (2014/89/EU) in July 2014. The Directive defines MSP as "a process by which the relevant Member State's authorities analyse and organise human activities in marine areas to achieve ecological, economic and social objectives" and the aim is to promote growth of maritime economies and sustainable development of marine areas and their resources. The provisions of the Directive apply to marine waters of Member States but not to coastal waters or parts thereof falling under a Member State's town and country planning system. For most Member States this means that MSP will begin at the low water mark and extend seaward to the limits of national jurisdiction (usually 200 nautical miles). Member States are encouraged to consider applying an ecosys-

4. Annex IV relates to the Assessment of Environmental Effects and Monitoring Efforts for Ocean Wave, Tidal and Current Energy Systems. *http://www.ocean-energy-systems.org/about-oes/work-programme/annex-iv-environmental-issues/*

5. The Annex IV participant countries are the United States, Sweden, Spain, South Africa, Portugal, Norway, Nigeria, New Zealand, Japan, Ireland, China, Canada and the United Kingdom.

tem approach and to promote coexistence of activities in their marine space. Member States must also take into account land-sea interactions, involve stakeholders, and ensure transboundary coordination and coherency with other approaches such as integrated coastal management.

In the **United Kingdom**, there are marine plan regions with an associated plan authority who prepares a marine plan for each of the marine areas. This framework is the result of recent legislation, the Marine and Coastal Access Act 2009, which provides a legal framework for marine planning and the creation of the Marine Management Organisation (MMO). The Act established the Secretary of State as the marine planning authority for the English inshore and English offshore marine planning regions, with the power to delegate certain marine planning functions. The Secretary of State delegated these functions to the MMO in April 2010. Marine plans, together with the Marine Policy Statement (MPS), underpin this planning system for England's seas. The MPS states that the marine planning process will manage competing demands in the marine area through an ecosystem-based approach. Plans will formulate and present outcomes for a marine plan area consistent with the MPS informed by evidence relevant to the plan area. In 2011, the Department for Environment, Food and Rural Affairs (Defra) recommended a series of marine plan areas for the English inshore and offshore marine regions to the MMO. The boundaries for these areas were identified following stakeholder and expert input and a specific consultation in 2010, resulting in 11 plan areas covering the seas around England. The 11 areas will ultimately result in 10 marine plans (in the northwest one marine plan will cover both the inshore and offshore regions). Currently, four marine plans have been developed (east inshore and offshore and south inshore and offshore) with all marine regions expected to have plans in place by 2021. In these regions the marine plan outlines priorities and directions for future development within the plan area and is used to inform marine users about suitable locations for their activities and where new developments may be sited. The plans created do not establish new requirements, but apply or clarify the intent of national policy in the marine plan regions, taking their specific characteristics into account. They will help to reduce the overall regulatory burden on applicants and users, by acting as an enabling mechanism for those seeking to undertake activities or development in the future, providing more certainty about where activities could best take place.

In Scotland, Wales, and Northern Ireland marine planning is the responsibility of the devolved administrations. In **Scotland**, the Marine (Scotland) Act was enacted in 2010 and provides the statutory basis for a streamlined marine planning and licensing system through the creation of a national or regional marine plan(s), a rationalized marine licensing process, and enforcement provisions. A new marine management authority for Scottish waters, Marine Scotland, was also established. Its Marine Licensing Operations Team (MS-LOT) is responsible for all marine licensing functions. A National Marine Plan (NMP) for Scotland was adopted on 25 March 2015 and laid before Parliament on 27 March 2015 (Scottish Government 2015). It covers all current Scottish marine sectors and reflects over-arching environmental objectives such as those from the EU's Marine Strategy Framework Directive. The plan outlines key objectives for the offshore wind and MRE sector in Scotland, covering not only marine planning aspects but also marine licensing and maximizing benefits from development of this sector at the regional level (Scottish Government 2015). The NMP will be supported by regional marine plans to cover 11 marine regions extending to the territorial sea limit (12 miles). These plans will be developed by local Marine Planning Partnerships comprising local authorities, inshore fisheries groups, and local coastal partnerships. The Marine Planning Partnerships have delegated powers from Scottish Ministers, and the plans developed will reflect local issues and needs in each region. The partnerships do not have consenting or licensing powers. The first regional plans are expected in 2015 and will cover the Shetland Isles and Clyde area.[6]

In **Wales,** the Welsh Government is currently developing a Welsh National Marine Plan (NMP), covering both Welsh inshore and offshore waters in a single plan. Relevant evidence has been collated and published in a Wales' Marine Evidence Report (Welsh Government, 2015c). The plan will introduce a plan-led approach to decision-making. The developing plan supports the sustainable use of Welsh seas and identifies opportunities for future use including in relation to marine renewable energy. In **Northern Ireland**, the

6. http://www.gov.scot/Topics/marine/seamanagement/regional

Marine (Northern Ireland) Act entered into force in 2013 to supplement provisions contained in the UK Act. The Northern Ireland Act follows a similar structure to those in other jurisdictions of the UK, providing a structure for marine plan development. The Act covers the Northern Ireland inshore region, marine conservation zones, and reform of marine licensing for certain electricity works. The Northern Ireland inshore region is defined as the territorial sea and the seabed adjacent to Northern Ireland, out to 12 nautical miles though jurisdictional issues in the border bays with the Republic of Ireland remain. Work on a marine plan for Northern Ireland commenced in March 2012 and is continuing to progress.

Portugal has been working on the creation of MSP for a number of years and now has a comprehensive nested system of marine plans. In 2008, an inter-ministerial order (Despacho n.º 32277/2008[7]) governing work on MSP was published. This order outlined the context, objectives, responsible authorities, and actions on MSP to be taken for continental territorial waters. After a three-month period of public consultation, an initial plan was published in November 2012 (Despacho n.º 14449/20128[8]) and is also available on the website of the Directorate-General of Marine Policies.[9] This plan provided for two types of mapping of marine activities, uses, and functions within coastal and marine areas in continental Portuguese territorial waters. One map covers current maritime spatial uses and activities and a second map covers potential future activities in the marine space. Both maps cover the majority of marine activities: conservation and heritage, fisheries and aquaculture, infrastructure, navigation, energy and geological resources. Defense and security uses along with tourism were included only in the map for the current situation, not future potential. The information from both of these maps was then combined in a final MSP map for three main types of marine space: 1) for protection, 2) for general use, and 3) for continental shelf. Within each of these categories a defined list of activities is permitted as shown in Table 8.1.

7. *http://www.dgpm.mam.gov.pt/Documents/POEM_Despacho_14449_2012.pdf*
8. *http://www.dgpm.mam.gov.pt/Documents/POEM_Despacho_14449_2012.pdf*
9. *http://www.dgpm.mam.gov.pt/Pages/POEM_PlanoDeOrdenamentoDoEspacoMarinho.aspx*

Because most marine activities in Portuguese waters occur in the territorial sea and the contiguous zone, precise management and regulatory measures were deemed necessary. Both general and sector-specific management guidelines were developed to guide sustainable development of marine activities and uses conducted in these spaces. The objectives of the sectoral guidelines are to guide the implementation and development of activities and uses in the maritime area; to ensure compatibility between different activities and uses and also between them and the main resources of the maritime area; and to enhance the development of synergies between the various sectors. The final plan still needs to be approved by the Portuguese Government and legislation enacted to enable it to enter into force. Key Portuguese legal instruments are listed in Table 8.2.

Table 8.1. Categories of marine uses in the Portuguese Marine Spatial Plan

Type of marine space	Area
Marine space for protection	Areas for defense and security Areas for conservation of nature and biodiversity Areas for underwater cultural heritage
Marine space for general use	Areas designated for specific uses Areas to be designated for specific uses Areas for multiple uses
Marine space of the continental shelf	Areas beyond 200 nautical miles

In **Sweden**, MSP is governed by the Swedish Environmental Code and has been augmented by specific MSP legislation in 2014, which recognizes the Government's view that MSP is a necessary tool for the conservation of marine areas and to help bring about cohesive marine management. Marine plans will be produced for the Gulf of Bothnia, the Baltic Sea, and the Skagerrak-Kattegat-North Sea area. They will cover Sweden's Exclusive Economic Zone (EEZ) and all areas in Swedish territorial waters within 1 nautical mile of the baseline that do not constitute private property. These plans will act as guidance documents to be applied in decisions concerning the sea. The government also has authority to adopt binding regulations to fulfil the

Table 8.2. Key Portuguese legal instruments on MSP

Legal Instrument	Key Provisions
Lei n.º 17/2014	Establishes principles for the planning and management of the national maritime space
Decree-Law 38/2015	Transposes the requirements of the EU Directive on MSP (2014/89/EU) Creates a one-stop-shop facility to administer licensing for marine projects Development of an online platform
Situation Plan	Distribution of existing and potential activities in the maritime space Developed by the assigned public authority
Allocation Plan but compatible it.	"Allocates" areas or volumes of marine space to activities not already identified in the Situation Plan It may be proposed by a public or private entity Needs to be accompanied by an Environmental Impact Assessment.

objectives of the plans, if that is deemed necessary. The Swedish Agency for Marine and Water Management (SwAM) is responsible for preparing the marine plans, but will be assisted by the County Administrations. National agencies responsible for specific national interests (including energy) as well as some other agencies will collaborate and cooperate with SwAM in the process. Municipal and regional authorities are also given the opportunity to participate in the work relating to preparation of the marine plans.

In **China**, marine functional zoning (MFZ) was first proposed in 1979. This involved a nationwide, comprehensive investigation of China's coastal zone and tidal flat resources with collaborative working across four departments. The purpose of this investigation was to develop a tideland resource zoning plan and to put forward a tentative plan for the rational utilization of China's coastal zones. Any use of the sea areas must comply with the MFZ plan established by the state. The plan acts as the basis for marine management and divides the sea space into different types of functional zones according to criteria related to geographical and ecological features, natural resources, current usage and socioeconomic development needs. MFZ applies to China's territorial sea only (i.e., 12 nautical miles). MFZ has become the basis for marine development planning, marine resource management, and the establishment of marine nature reserves in China and has been undertaken in a series of "rounds." Following the State Council's institutional reorganization in 1988, the State Oceanic Administration (SOA) was given responsibility for organizing the designation of major comprehensive uses of sea areas and for determining marine functional zones within the coastal provinces, autonomous regions, and municipalities. Two rounds have taken place to date, and a third round between 2009 and 2012 was planned jointly among the relevant authorities and coastal local governments in accordance with the Sea Area Use Administration law, the Law on Marine Environmental Protection and the Sea Island Protection Law. This was approved in March 2012.

The countries tabulated in Table 8.3 responded that they had no formal MSP in place at this time but had explored the possibility in certain contexts or were working on how MSP could be implemented in the future. This can be contrasted with the information in Table 8.4 where respondents from South Africa, Norway, New Zealand, and Canada stated that while they did not have MSP they all had integrated coastal plans in place that can address marine uses and their management to varying extents.

In the **United States** at the state level, Oregon and Washington are both engaged in Coastal and Marine Spatial Planning (CMSP) activities, while California continues to be engaged in sector-specific MSP under the Marine Life Protection Act. In 2013, Washington State completed its first round of MSP, which consisted of data and capacity analysis, education and outreach, development of data management and display tools, and a series of stakeholder meetings of the Washington Coastal Marine Advisory Council. Although the

Table 8.3. Countries with no formal MSP.

Country	Status	Ongoing Approaches
Spain	No formal MSP	◆ Feasibility of MSP explored for siting wave energy devices on the Basque continental shelf (Galparsoro et al. 2012) ◆ Protection of the Marine Environment Act (2010) includes principles and procedures for planning in the marine environment and transposes the Marine Strategy Framework Directive (MSFD) into Spanish law.
Ireland	No formal MSP	◆ Government is working on reform of the marine licensing process and new legislation is expected in 2015. ◆ "Harnessing Our Ocean Wealth," (HOOW) a national integrated marine plan, sets out the government's vision, goals, and "enabling" actions needed to realize the country's maritime potential (Government of Ireland 2012). ◆ HOOW identifies the need to develop an appropriate MSP framework for Ireland in the short to medium term. ◆ Enablers Task Force recommends a national marine spatial plan covering Ireland's marine waters at a strategic level, with more detailed plans to be developed later at sub-national level as required (Enablers Task Force 2015).
Japan	No formal MSP	◆ Basic Act on Ocean Policy 2007 provides a legal basis for the integrated management of coastal areas and river basins.
Nigeria	No formal MSP	◆ Governance of the marine area is fragmented with multiple authorities having legal remits and responsibilities.
United States	No formal MSP	◆ Considerable political barriers, multi-jurisdictional and sector-specific nature of jurisdiction over marine space do not lend themselves well to prescriptive MSP in the United States. ◆ Most effort focuses on promoting consistency between State and Federal agencies. ◆ National Ocean Policy (NOP) Implementation Plan in 2013 describes specific actions federal agencies will take to address key ocean challenges. • Results in USA being divided into nine regions and encouraged the formation of Regional Planning Bodies (RPBs) • Each RPB is composed of federal, state, local, and tribal (indigenous) representatives. • Currently, each of the RPBs is at different stage in the planning process; the Northeast and Mid-Atlantic are furthest along and in the development stage for regional ocean plans.[10] • The RPB for a specific region has no regulatory authority.

10. *See the New England (http://neoceanplanning.org/) and mid-Atlantic data portals (http://midatlanticocean.org/data-portal/).*

Table 8.4. Equivalent approaches to MSP.

Country	Law and Policy	Implications
South Africa	Integrated Coastal Management Act, 2008: defines the coastal zone as the area comprising coastal public property, the coastal protection zone, coastal access land and coastal protected areas, the seashore, coastal waters and the EEZ and includes any aspect of the environment on, in, under and above such area.	• National Coastal Management Programme (NCMP) 2013 to 2017 • Aims to resolve existing management problems and user conflicts • Outlines long-term development and management objectives • Spatial planning in the coastal zone seaward of high water mark is sectoral planning that takes place independently of each other (DEA 2014).
Norway	Planning and Building Act: used for planning to one nautical mile from the baseline of the seashore Beyond the 1 nautical mile limit to the 200 nautical mile limit: no specific legislation for MSP, but there is a basis in parliamentary reports and government declarations.	• Regional, inter-municipal and local plans but these vary in content and quality • Local administrations have jurisdiction 1 nautical mile mile offshore but plans usually apply to the landward side of the baseline only.
	Norwegian Marine Resources Act 2009 (Havressursloven)	• Provides for Integrated Management Plans • Primarily to halt loss of biodiversity and management decisions are taken with this objective in mind. • Plans are advisory in nature. • Three plans developed to date
	Barents Sea (Norwegian Ministry of the Environment 2011)	• Covers all existing economic sectors including oil and gas, marine transport and marine conservation as well as fisheries.
	Norwegian Sea (Norwegian Ministry of the Environment 2009)	• Seeks to protect important areas for biodiversity but also to facilitate the coexistence of different activities with the plan area • Contains spatial management measures for hydrocarbons, fishing, marine transport, and nature conservation.
	North Sea and Skagerrak (Norwegian Ministry of the Environment 2013)	• Sea area is shared by eight countries, so strong international cooperation is highlighted in the plan.
New Zealand	Resource Management Act (RMA) 1991	• Enables marine planning in a regional fashion through coastal plans. • Coastal plans are developed by regional councils and unitary authorities. • Includes objectives, policies, and rules for what activities are permitted, controlled or prohibited within plan area.
	New Zealand Coastal Policy Statement (NZCPS)	• Plans made under the NZCPS and RMA have a seaward limit of 12 nautical miles. • Inland scope that varies according to local geography.
	Hauraki Gulf – Tikapa Moana region Marine Spatial Plan	• Most intensively used marine areas • Country's first marine park (2000) • Developed in a "bottom-up" way • Managed by a Stakeholder Working Group • Non-statutory
	National Science Challenge	• Sustainable Seas National Science Challenge • Aim to enhance utilization of marine resources within biological and environmental constraints. • Ecosystem-based approach to future oceans management

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Country	Law and Policy	Implications
Canada	Oceans Act 1996 Canada's Oceans Strategy (2002) Ocean Action Plan (2005)	• Five Large Ocean Management Areas (LOMAs) created to plan and manage marine activities. • Integrated approach • Different departments within the provincial governments exercise authority over different spatial components of the marine area.
	1. Placentia Bay and Grand Banks LOMA 2. Scotian Shelf LOMA 3. Gulf of St Lawrence LOMA 4. Beaufort Sea LOMA 5. Pacific North Coast LOMA	• Risk-based management approach to identify and prioritize key management themes deriving from human activity interactions with the ecosystem components • Operate within existing jurisdictional landscapes • Regulatory authorities at different levels of governance are responsible for implementation of plan goals through management policies and measures under their remit. • Biophysical assessment • Social, Economic, and Cultural Overview and Assessment (SECOA)

Legislature did allocate renewed funding to support continued CMSP activities, state activities are currently stalled as state agencies and the Governor determine a path forward (Van Cleve and Geerlofs 2013). Rhode Island has developed the Special Area Management Plan (SAMP) (Coastal Resources Management Council 2010). Johnson (2014) states that Rhode Island legislation requires that the state preserve, protect, develop, and restore coastal resources for present and future generations through comprehensive long-range planning and management, using preservation and restoration of ecological systems as the primary principle to measure and regulate environmental alteration of coastal resources. The Massachusetts Oceans Act of 2008 led to the creation of the Ocean Advisory Commission to advise the Secretary of Interior in developing an ocean management plan. The Act sets out the framework for development of a comprehensive plan that supports ecosystem health and economic vitality, balances existing ocean uses, considers future needs, and addresses values such as the public trust, sound management practices, biodiversity, fostering sustainability, and preserving public access and public participation. The plan was completed in 2009 and was incorporated into the Massachusetts coastal management plan.

8.2 INCLUSION OF MARINE RENEWABLE ENERGY IN MARINE SPATIAL PLANS

Marine renewable energy is still a developing sector in most parts of the world and as such it is not yet fully integrated into the various planning systems that apply to marine waters. Where marine plans already exist they do tend to reflect operational offshore wind farms (O'Hagan 2012). Likewise if a country has functioning test sites for research and development of wave and tidal energy, they are included in existing marine plans as an existing use. What is clear from the survey responses is that many national planning systems, whether through marine spatial plans or other coastal plans, are inherently flexible and can be adapted to reflect the operation of new marine activities such as energy production. Because MSP is a future-oriented approach to management and takes a planning horizon of up to 20 years in the future it can facilitate planning for new and emerging technologies like wave and tidal energy.

The MPS in the **United Kingdom** states that marine plans should take account of and identify areas of potential for the deployment of different renewable energy technologies (HM Government 2011). Renewable energy has been categorized into offshore wind, wave, and tidal for the purposes of marine planning.

The MMO undertook a Strategic Scoping Exercise prior to beginning work on the East marine plans, which was updated prior to beginning the South Marine Plans, and this provides a national picture of how activities, resources, and ecosystems vary across each of England's 11 marine plan areas to understand the characteristics of each. It also identifies what renewable energy is present or has potential within each plan area. Because offshore wind is the only technology that is currently deployed at a commercial scale within English waters it is more prominent within the marine plans. In the East it was considered to be one of two transformational sectors over the 20-year vision of the plan and as such there are two dedicated wind policies within the plan area. The potential for tidal-stream energy generation has also been recognized as having significant resource potential (through work undertaken by The Crown Estate) and a tidal policy is in place to ensure that areas of resource are available for exploitation. The limited scale of resource and lack of maturity in the sector for wave energy means that there was not sufficient justification for a dedicated or stand-alone policy. Consents for nationally significant infrastructure projects, including the larger offshore renewable energy and port developments, need to be determined in accordance with the UK Planning Act 2008. The broader role of renewable energy in improving air quality compared to fossil fuel energy is highlighted in the MPS. It states that marine planning has an important role to play in facilitating climate change mitigation, through actions such as offshore renewables and carbon capture and storage.

In **Spain**, in the case of the southeast part of the Bay of Biscay in the Basque Country, an analysis of the creation of the Biscay Marine Energy Platform (BIMEP) was analyzed in the MESMA project as a case study (Monitoring and Evaluation of Spatially Managed Areas; *www.mesma.org*). This developed a Suitability Index for WECs that took into account the technical, environmental, and socioeconomic restrictions on WEC deployment in an integrated way. The analytical results were combined with the accessible energy potential and the technically exploitable wave energy potential and ultimately enabled wave energy developers and regulators to identify the most suitable sites where subsequent studies should be undertaken to facilitate development. Elsewhere in Spain, the Ministry of Industry, Energy and Tourism conducted a Strategic Environmental Assessment (SEA) on offshore wind in 2009 (Ministerio de Industria, Energía y Turismo 2009) in order to determine areas of the public maritime domain that had favorable conditions, including little or no expected environmental effects, for the installation of offshore wind farms. It categorized areas according to their suitability, with unsuitable or "exclusion zones" colored red on a map and suitable areas colored green. Areas that may be suitable but that are subject to additional requirement or conditions are colored yellow (Ministerio de Industria, Energía y Turismo 2009).

In **Portugal**, within the preliminary marine spatial mapping exercise and more recently in the situation and allocation plans described above, MRE is included under the "Energy and geological resources" theme, which covers both offshore wind and wave energy. The MSP maps published reflect the areas that are currently used for marine renewables (Peniche, S. Pedro de Muel and Aguçadoura). Potential areas for the development of offshore wind and wave energy are included in the map covering potential future uses of the maritime space. The final MSP mapped MRE under the category "areas designated for specific uses," which covers a large part of the available coastal area.

In **Ireland**, there is one operational test site for wave energy (Galway Bay), and a second full-scale test site is in the final stages of development (Atlantic Marine Energy Test Site – AMETS). While there is no national MSP in place yet, there is a dedicated plan for MRE in the form of the Offshore Renewable Energy Development Plan (OREDP) (DCENR 2014). The OREDP sets out the key principles, policy actions, and enablers for delivery of Ireland's significant potential in this area and provides a framework for the sustainable development of Ireland's offshore renewable energy resources.

The marine plans developed for waters in **Sweden** will include offshore wind and wave energy. Currently, tidal energy is not relevant to the Swedish situation, though this could change in future. The Swedish Energy Agency has declared specific national interest areas for offshore wind that are considered to have a significant physical wind resource suitable for future exploitation. Provisions related to national interest areas are derived from the Swedish Environmental Code and state that such areas shall be protected from measures that may damage their value. According to the MSP regulation, these national interest areas must be balanced with other national interests such as defense, fisheries, and shipping routes. In 2013, 27 such offshore wind areas were designated with an approximate total sea area of 4000 km2. The selection of areas was based on a number of criteria including a wind speed of at least 8 m/s, a connected area of at least 15 km^2, and a water depth of no more than 35 m. As yet no areas of national interest have been designated for wave energy. Doing so is hindered by the fact that no systematic resource assessment and mapping exercise has been conducted to inform future site selection and investigation for wave energy development.

In **Norway**, a new legal instrument related to offshore renewable energy production (the Offshore Energy Act) entered into force in 2010. The Offshore Energy Act provides a framework for regulating offshore renewable energy production, and as a general rule applies outside the baselines and to the continental shelf. It can also apply inside the baselines (i.e., above the low water mark/straight baseline). A strategy for offshore renewable energy accompanied the Bill (Norwegian Ministry of Petroleum and Energy 2009). Section 2.3 of the Act provides that renewable energy production may only be established after public authorities have opened specific geographical areas for license applications. This is to ensure that energy production takes place in areas where the potential for conflict is as low as possible. At local and municipal levels, MRE is not usually an issue for local spatial planning because it is taken care of by the energy authorities through the Energy Act. Local and regional authorities can participate in that process and give their opinion on the plans. Further offshore, the Integrated Marine Plan for the Norwegian Sea states that offshore renewable energy production will be facilitated but should take into account environmental considerations and other activities (Norwegian Ministry of the Environment 2009). Within the Barents Sea – Lofoten Integrated Management Plan area, there are no offshore energy plants but, theoretically, there is substantial potential for MRE production (Norwegian Ministry of the Environment 2011). Within that area in 2010 a working group consisting of all the relevant statutory authorities produced a report on 15 proposed areas for impact assessments in connection with offshore wind energy. After the impact assessments, the Water Resources and Energy Directorate recommended that priority should be given to a total of five areas, four of which are in the North Sea. Two prototype tidal plants operate within the Barents Sea – Lofoten Integrated Management Plan (Norwegian Ministry of the Environment 2011).

In **Japan**, MRE is at the very early stages of development. It has been incorporated into certain specific locations such as at ports, but there is no clear way in which MSP includes the needs of the MRE sector. In **China**, a special functional zone was created for MRE. According to the Technical Guidelines for Marine Functional Zoning and the Technical Requirements for Provincial Marine Functional Zoning, all sea areas of China area divided into eight "Class I" functional zones and 22 Class II functional zones. The MRE zone is a sub-zone under the Class I zone of "mines and energy zone." Sea areas that have rich and exploitable MRE (such as wave, tidal current and tidal energy, salinity, and temperature gradient energy) are classified as Renewable Energy Areas. Because offshore wind energy is different from the other sources and there is a larger resource, its development is viewed as compatible with some other sea uses and no special basic functional zone is defined for it.

In **South Africa**, currently all renewable energy activities are governed by the National Energy Act of 2008. Many existing regulations, norms and standards, and guidelines are applicable to renewable energy activities in the coastal zone including SEA. The Department of Environmental Affairs is working on an SEA of wind and solar photovoltaic energy. The aim of this assessment is to identify strategic geographical areas on land that are best suited to large-scale wind and solar photovoltaic energy projects, referred to as Renewable Energy Development Zones. As part of South Africa's National Coastal Management Programme, a key aim is to strengthen partnerships between entities working in the marine space and to establish Memoranda of Understanding (MoUs) with other departments governing the management and control of activities in the coastal zone that are not legislated for under the Integrated Coastal Management (ICM) Act; e.g., mining, infrastructure development, fisheries and marine aquaculture, MRE, state assets, shipping, oil and gas, and biodiversity and protected areas planning. In the future, therefore, there is an option for MRE to be included. The Act itself recognizes that future guidance on MRE activities in the coastal zone will need to align regulations, norms, standards, and guidelines that apply to renewable energy activities in the coastal zone under the National Energy Act with requirements under the ICM Act (and National Environmental Management Act).

MRE is at a very early stage in **Nigeria** and so far attention has focused on Ocean Thermal Energy Conversion (OTEC). The country also has a tidal resource but the data are not yet sufficient to determine the extent of the resource. The Nigerian Institute for Oceanography and Marine Research (NIOMR) has been collecting oceanographic data around the coast of Lagos State, but the temporal scale of the data is not always consistent and the spatial scale is limited to that area. With respect to OTEC, a preliminary analysis indicates that Nigeria can develop over 10 separate multi-product OTEC plants each generating 100–500 MW, along the coastal shores of the country on an incremental basis as funds permit. Recently, a consortium, FOT-K[11], and NIOMR received government endorsement and the first phase of feasibility studies is under way. The studies are expected to identify the most suitable sites for OTEC plants in offshore Nigerian waters. The economic viability of OTEC plants on the continental shelf is also being explored. NIOMR has a designated technical team working on this in collaboration with the FOT-K consortium. To assist in the realization of OTEC, the federal government of Nigeria is considering setting up a Centre for Ocean Renewable Energy Resources (CORER) to be co-located within NIOMR in Lagos. CORER is expected to oversee all OTEC initiatives from research, feasibility/development studies, conceptual design, engineering, through deployment of the integrated OTEC facilities, including connection to the national grid and facility management, as well as any other ocean-related renewable energy resources suitable for Nigeria. No final decision about the creation of CORER has been made at the time of this writing (September 2015).

In **New Zealand,** the MSP for Hauraki Gulf incorporates sustainable energies but does not specifically include marine energy. This could change as MRE technologies reach commercial maturity. In relation to the aquaculture sector, for example, resource consent applications for marine farms can only be made within aquaculture management areas identified in regional coastal plans. As a result of the proposed reforms contained in the Aquaculture Legislation Amendment Bill (No 3), resource consent applications for marine farms will be possible anywhere within the Gulf where marine farming is not explicitly prohibited in the regional coastal plan. More generally at the national level, the New Zealand Coastal Policy Statement (NZCPS) contains spatial provision for a number of marine uses, including the spatial identification of appropriate places for aquaculture (Policy 8), provision for the operation and development of ports (Policy 9), and consideration of the potential for energy generation (Policy 6(1)) (New Zealand Government 2010).

In **Canada**, the Large Ocean Management Areas (LOMAs) are hundreds of square kilometers in size and typically host a range of marine activities including renewable energy. In each LOMA, management objectives designed to ensure the health of the ecosystem are identified and accompanied by socioeconomic objectives, based on the Social, Economic, and Cultural Overview and Assessment (SECOA). For the majority of the LOMA plan areas, MRE is not mentioned. The Pacific North Coast Integrated Management Area Plan (2013), which covers waters from the north Canadian border with Alaska to Vancouver Island, where there is a MRE resource, has representatives from both the wind energy group and ocean energy sector on its Integrated Oceans Advisory Committee. On Canada's East Coast, the Eastern Scotian Shelf Integrated Management Initiative published in 2008 was evaluated in 2013 and recognizes the opportunities for new marine activities within that LOMA. The Eastern Scotian Shelf LOMA includes Nova Scotia, where the Department of Energy is currently developing a planning system for the designation of areas for MRE development. The system designates a system of consecutively smaller areas in which development may occur until it reaches the individual site license level. Prior to any area being designated there is a requirement to complete an SEA. At the highest level there are Areas of Marine Renewable Energy Priority (AMREP) that are broad-scope planning areas where the next level of planning area can be designated, namely Marine Renewable Electricity Areas (MREAs). MREAs are areas where development licenses can be issued. Within the MREAs, licenses may be issued that can encompass the entire MREA or a portion of the total area. As set forth in draft legislation, the creation of MREAs must be done in

11. *http://www.fot-kconsortium.com/Energy.aspx*

consultation with the Department of Natural Resources and the Department of Fisheries and Aquaculture. The federal government must also be consulted about commercial fisheries and maritime transportation concerns. There is also the duty to consult the Aboriginal community about the designation process as well, but that community has no veto power.

In the **United States**, BOEM created Renewable Energy Task Forces specifically to convene stakeholders to evaluate areas of least conflict for consideration of MRE. To date, a majority of the interest received has been focused on offshore wind energy. BOEM also has authority to issue a renewable energy lease for marine and hydrokinetic (MHK) technologies. Developers have indicated limited interest in wave energy to BOEM, but the Florida BOEM Renewable Energy Task Force has focused on a proposal to capture ocean current energy from the Gulf Stream off of the southeast coast[12]. In addition, most of the states that developed their own marine plans were heavily motivated by renewable energy interests. Both the Northeast and Mid-Atlantic Regional Planning Bodies (RPBs) support MSP data portals that contain specific renewable energy sections outlining specific attributes applicable to development and planning. In 2009, Oregon initiated a process to update its existing Territorial Sea Plan, which governs use of the ocean resources out to 3 nautical miles offshore, to establish state governance of MRE. The outcome is a comprehensive spatial plan in map format, MRE project siting policies, procedures, operating requirements, and project review standards for protecting other ocean uses and resources. The new regulatory pathway for state permitting, together with the MoU between Oregon and the Federal Energy Regulatory Commission (FERC) was signed in 2008 (Van Cleve and Geerlofs 2013). In Washington State, at the direction of the Washington State Legislature, agencies, tribes, and coastal stakeholders are engaged in an MSP process that will include maps depicting "appropriate locations with high potential for renewable energy production with minimal potential for conflicts with other existing uses or sensitive environments," and a framework for coordinating timely local and state agency review of proposed MRE projects while considering environmental impacts and existing uses (Van Cleve and Geerlofs 2013).

12. *http://www.boem.gov/First-Florida-Intergovernmental-Renewable-Energy-Task-Force-Meeting-Dec-11-2014/*

8.3 USE OF SCIENTIFIC INFORMATION IN MSP FOR MARINE RENEWABLES

Scientific data and information are fundamental to the development and implementation of MSP. Having scientists involved in the plan development phase can help to identify gaps in knowledge and future research priorities. A large proportion of respondents to the survey indicated that there are a number of data gaps in relation to their national and local marine environments. This varies by location and can be addressed through specific research programs and projects, such as is the case in Scotland. In other countries (e.g., South Africa and Norway), the aspiration to implement MSP has acted as a driver for the collection and consolidation of marine data.

In the **United Kingdom**, marine plans must be based on a sound evidence base, and the MMO has been working closely with many partners and stakeholders since the start of the planning process to gather the best available evidence to better understand the activities, resources, and ecosystem in the South Marine Plan areas. Evidence was summarized in the East Evidence and Issues/South Plans Analytical Report, setting out the range of evidence used for marine plan preparation, including spatial data, third-party research reports/guidance documents, specifically commissioned research, and national/sub-national policy (MMO 2012 and 2014b). To support integration between land and sea, there is a duty to ensure all marine plans are compatible with plans developed by local planning authorities. Additional plans assessed included Local Transport Plans, River Basin Management Plans, Shoreline Management Plans, and Estuary Management Plans. Spatial information related to sub-national plans can also be found on the Marine Planning Portal[13]. For certain activities, such as marine aggregates, this compatibility and influence may extend to plans and authorities outside of the marine plan area. Strategic research programs in the UK, coordinated by Defra and National Environmental Research Council, have endeavored to address some of the uncertainties around the effects of MRE devices, including their environmental interactions, socioeconomic impacts, and physical impacts of structures on the environment (e.g., the Engineering and Physical Sciences Research Council SuperGen initiative). The majority of this work has focused on improving reliability and reducing costs for industry as well as reducing the costs of consenting MRE developments and making the process more straightforward. There have been concerted efforts to engage with developers and regulators throughout these programs which will later inform MSP.

Regionally, in **Wales** a Strategic Scoping Exercise (SSE) was carried out to review and analyze the available evidence for Welsh waters (Welsh Government 2015a). The government has also commissioned a number of research projects to fill specific evidence gaps, such as those relating to aquaculture, seascapes, and recreational fishing (Welsh Government 2015b). A dedicated portal for marine data and information has also been developed as part of this process[14]. In S**cotland,** sectoral marine plans are being developed for offshore wind, wave, and tidal energy sources. These plans have each been the subject of an SEA, Habitats Regulations Appraisal and socioeconomic assessment at a strategic level. Gaps identified during these assessments have informed the prioritization of research so as to inform the sectoral marine planning process and also wider national marine planning. Marine Scotland established the Marine Renewable Energy Programme in 2011 to give scientific support to policy development and licensing of MRE production. This program seeks to develop.

- risk analysis protocols to guide development applications, cover pre-development data requirements, data assessment methods, approaches to Habitats Regulations Assessment and Appropriate Assessment, mitigation, and post-development monitoring; and
- tools and data assessment methods: including EIAs for the identification of "preferred" development areas in the context of marine planning, resource assessment, and estimation of carrying capacity.

The Scottish Marine Renewable Research Group, led by Marine Scotland but with involvement from other Scottish and UK organizations, works on the uncertainties related to the interactions between wave and tidal energy and the marine environment. To date investigations related to potential impacts between seabirds, marine mammals, habitats, and marine renewables, as well as generic research into the potential effects on the marine environment as a whole, have been conducted. There is also a dedicated Marine Mammal Scientific Support Research Programme focusing on marine mammal interactions with MRE devices, unexplained seal deaths, and decline in common seal numbers—the results of which will inform Scottish marine policy and wider marine mammal management and conservation (The Scottish Government 2012).

In **Spain**, for the BIMEP marine energy platform, a spatial planning approach was taken so as to achieve consensus among the sectors working in that marine area currently and also to assist in the identification of the most suitable locations for wave energy farms in the future. Seventeen data layers covering 10 technical, 4 environmental, and 3 socioeconomic factors were included in a dedicated geographic information system (GIS). Algorithms in the GIS were then used to assess the total theoretical energy potential and the accessible theoretical energy potential. Constraint maps were produced indicating where conflicts could be expected, such as in areas of navigation or designated marine protected areas (Galparsoro et al. 2012). In **Portugal,** the MSP process began with a characterization phase where scientific information describing the extant marine resources and marine environment were compiled. This brought together information from several different ministries, which was then incorporated into the analysis. **Ireland** has completed a seabed survey of its entire EEZ area and is working on completing seabed mapping for its inshore areas. This information is all freely available and will inform the future development of marine spatial plans in the country. There is also strong scientific and technical research capacity in both MSP and MRE in many universities and third level institutions.

In **Sweden**, some of the planning evidence collected during the MSP preparatory work is based on scientific evidence. There is uncertainty concerning quantitative information regarding the technical potential for wave power (Swedish Agency for Marine and Water Management 2014). To address this gap, the Swedish Energy Agency is planning to investigate the wave and current resource around Sweden and it will be incorporated into the MSPs developed at a later stage. With respect to the marine environment, Sweden has no national program for mapping and monitoring marine habitats though progressive implementation of EU Directives on these topics are changing this position. In **Norway**, a vast amount of scientific were integrated into the reports and white papers associated with the integrated management plan for each sea area. Sector-specific scien-

13. *http://lle.wales.gov.uk/apps/marineportal/#lat=52.5145&lon=-3.9111&z=8*
14. *http://lle.wales.gov.uk/apps/marineportal/#lat=52.5145&lon=-3.9111&z=8*

tific reports also describe the data and analyses in more detail and they can be used to inform local planning and decision-making. Most recently, Norway has been augmenting its marine environmental data through, for example, national programs such as Mareano[15], which maps bathymetry, topography, sediment composition, biodiversity, habitats, and biotopes as well as pollution in the seabed in Norwegian offshore areas. This in turn informs the management of activities like fisheries as well as future petroleum activities. A new program called "Coast-Mareano" will advance mapping of nearshore waters, with a coastal pilot area now established at Sunnmøre, representing cooperation between the Runde Environmental Centre, the national mapping authority, and the Geological Survey of Norway. This will encompass new bathymetric surveys and the methodologies used can be transferred to other coastal regions.

In **Japan**, films based on in situ observation data and numerical simulations have been used to explain the operating principles and effects of MRE devices on the environment to local residents, fishermen, and other marine users. In **China**, the Technical Guidelines for Marine Functional Zoning and the Technical Requirements for Provincial Marine Function Zoning list all the data and materials required for the zoning and the methods used. Base maps and remotely sensed and satellite imagery are all used as a foundation for the maps produced. Information about the area's socio-economic characteristics and current marine usages patterns will inform the documentary reports accompanying the maps. This also includes an assessment of the physical environment, demands for sea use, environmental protection requirements, commercial fishing activities, marine reclamation, etc., to present as comprehensive and detailed basis for future zoning as possible.

In **South Africa**, no national MSP system exists yet, but through the Operation Phakisa initiative and its key objectives of establishing MSP and developing a national ocean and coastal information system as well as extending Earth observation capacity, this is likely to change in the near future. There are currently approximately 20 key departments and institutions with distinct roles and maritime policies applicable in the marine environment. With an extensive marine area, much of South Africa's ocean space has not been studied or surveyed and there is a need to consolidate survey, research, and monitoring programs that are under way or have been completed (Marine Protection Services and Governance 2014). As identified action items in Operation Phakisa, these activities will progress in parallel during 2015 and 2016 with consolidated existing marine environmental and socioeconomic data acting as a basis for MSP development. In **Nigeria**, the NIOMR has been collecting scientific data, particularly tidal observations, since 2003, but there is no national marine planning process that these data or information can feed into at this time. An analogous situation exists in **New Zealand** where no national MSP system is in place. In the Hauraki Gulf/Tikapa Moana area, where the development of a marine spatial plan is under way, a preliminary review of MSP initiatives and their possible application to that region highlights the role of science and the possibility of formalizing a Hauraki Gulf Science Advisory Group to oversee any necessary scientific work (Hauraki Gulf Forum 2011).

In **Canada**, managing the LOMAs is a four-step process. After initiating the planning process and establishing the necessary governance structures, information about the ecosystem, social, economic, and cultural features associated with each LOMA is gathered. It is compiled into ecosystem overview and assessment reports and social, economic, and cultural overview and assessment reports, respectively. Once the information compilation and analysis have been completed the most ecologically significant areas are identified as well as conservation objectives for the areas. These objectives guide decision-making in the LOMA to ensure that the health of the ecosystem is not compromised by human activities. Socioeconomic objectives are also agreed upon and both sets of objectives are contained in the over-arching integrated management plan for the LOMA. The effectiveness of the plans is monitored and evaluated over time and they can be adapted to reflect new scientific information or changing circumstances. To date in Nova Scotia, scientific information about where and how to site MRE projects is largely directed by the Department of Fisheries and Oceans, the Canadian Hydrographic Service, and the Geological Survey of Canada. Data are based on surveys and information collected from fisheries activities. The Department of Fisheries and Oceans holds and has access to a wide range of fisheries and habitat related information, which can be incorporated into any permissions or advice they provide on MRE projects.

15. *http://mareano.no/en/start*

In the **United States**, several government-supported programs such as the National Ocean Council and the associated RPBs along with federal agency environmental programs work to catalog data available for MSP and make them accessible to the public through online resources such as the marine cadastre. Through this process, data gaps are identified, prioritized, and addressed by federal research programs such as BOEM's environmental studies program and state-sponsored activities. The Rhode Island SAMP provides a good example of how state activities have assisted in collecting spatially explicit data for MSP. The SAMP research priorities include initiatives that range from assessing the current spatial and temporal patterns of bird abundance to employing oceanographers to characterize the physical oceanographic characteristics of the region. Scientific information also played a key role in the development of the Massachusetts Ocean Management Plan. The plan creates three management areas within the state waters: prohibited, renewable energy, and multi-use. Each area was defined using the latest scientific information and spatially explicit data. The Massachusetts Plan was developed in coordination with an Ocean Science Advisory Council of nine scientists with expertise in marine sciences and data management to review data sources, help develop the baseline assessment and characterization of the ocean planning area, identify questions to improve understanding of natural systems and human influences, and contribute to a long-term strategy for addressing information gaps.[16]

8.4 CUMULATIVE IMPACTS IN MARINE SPATIAL PLANNING

Traditional sectoral-based management of marine activities has not always considered the effects of multiple developments on other human activities or the marine environment. In the EU, both the Environmental Impact Assessment Directive and the Habitats Directive require the assessment of cumulative impacts. Experience to date, with the EIA in particular, indicates that cumulative impacts are either not taken into account at all or not considered sufficiently (EC 2009). Ecosystem-based management includes all components of the ecosystem and should consider the cumulative impacts of different sectors on the marine environment. As a tool for implementing ecosystem-based management, MSP can also be used to assess the cumulative impacts in space and time of current and future economic developments on ecological processes in marine areas. Approaches to doing this are still under development in many countries; some places, e.g., in the EU, are using or adapting existing tools like SEA and others, e.g., Scotland, are trialling risk assessment-based processes.

In the **United Kingdom**, the MPS states that "Marine Plans should provide for continued, as well as new, uses and developments in appropriate locations. They should identify how the potential impacts of activities will be managed, including cumulative effects. Close working across plan boundaries will enable the marine plan authority to take account of the cumulative effects of activities at plan boundaries. The consideration of cumulative effects alongside other evidence may enable limits or targets for the area to be determined in the Marine Plan, if it is appropriate to do so" (HM Government 2011). In practice cumulative impacts are difficult to quantify in a data-poor environment, but the process of developing regionally specific marine plans allows for the gathering of data and stakeholder input, which in turn identifies areas that are either sensitive to cumulative impacts or areas that are currently very busy. In addition to using the best available evidence, the MMO has developed the Marine Information System and the Planning Portal, which aid both developers and decision-makers' understanding of cumulative impacts. The MMO are also members of the recently formed Cumulative Effects Assessment Working Group, led by Defra, ensuring that the emerging advice can be incorporated into developing marine plans and into adopted marine plans at the review stage. RenewableUK, the largest renewable energy trade organization, published guidelines on cumulative impact assessment for offshore wind farms in response to the fact that it was causing considerable delays, of up to 42 months, in some consenting procedures for offshore wind farms (RenewableUK 2013).

In **Spain**, for the BIMEP cumulative impacts were considered through constraint mapping, which was produced using the customized GIS. Nationally this has not been considered fully. The SEA for offshore wind in Spain did not consider cumulative impacts. In contrast, the SEA conducted on the marine spatial plan for

16. *http://www.mass.gov/eea/waste-mgnt-recycling/coasts-and-oceans/mass-ocean-plan/*

Portugal addressed some cumulative impacts. This will also be the case for **Sweden** because, under the EU MSP Directive, the marine spatial plans developed will be subject to an SEA, which in turn will inform SwAM in elaborating the plan proposals as well as the government in adopting them. In order to support the SEA an analytic tool for semi-quantitative assessment of cumulative effects will be developed and used. This will enable the identification of spatially defined impacts/risks for different planning alternatives. Environmental indicators will also be incorporated, based on the EU's Marine Strategy Framework Directive. The analytic tool is an adaptation of existing scientific tools for cumulative effects assessment. In **Ireland**, there is no system in place as yet to deal systematically with cumulative impacts though, as an EU Member State, such impacts should be included in any SEA and EIA carried out. Under the integrated management approach in **Norway**, all activities in the plan areas are to be managed within a single context so that the total environmental pressure from activities should not threaten the ecosystems. Each Integrated Plan has a section on cumulative impacts outlining current cumulative impacts, how they were assessed, and those effects expected in the longer term, such as those from climate change, ocean acidification, etc., so as to comply with the provisions of the Nature Diversity Act. The assessment of cumulative effects forms the basis for the overall assessment of the need for measures and tools presented later in the Integrated Plan. In the Norwegian Sea the greatest cumulative effects are on certain fish species, seabird species, and seabed habitats, and accordingly there are specific actions identified for government in the management plan (Norwegian Ministry of the Environment 2009).

In both **South Africa** and **Japan**, there is no formal MSP system, which may make it more difficult to address cumulative impacts in the marine environment and necessitate a stronger reliance on tools such as EIAs and SEAs. In **Nigeria** any situations where cumulative impacts have arisen may have been dealt with independently, depending on who has the applicable data and information. In **China**, MFZ pays particular attention to the management of marine reclamation and protection of the marine environment. In view of the cumulative impacts of marine reclamation on the marine environment, quantitative objectives for the total quantity of marine habitat that can be reclaimed are set in the marine functional plans, based on surveys and studies on the capacity of the marine environment. This is to ensure that marine reclamation activities will not exceed the carrying capacity of the marine environment and in that way protect the marine environment. In **New Zealand** the possibility for cumulative impacts from multiple marine activities is acknowledged, but the tools are yet to be developed that adequately deal with several types of impacts. It is anticipated that this will be an area of focus under the new National Science Challenge "Sustainable Seas," which aims to enhance the use of New Zealand's marine resources, while ensuring that the marine environment is understood and managed sustainably now and in the future. The program recognizes that this requires a new way of managing marine resources and their usage involving the Māori, communities, industry, and scientists. This will be addressed through the development of a strategy and tools for the integrated management of the sea and its resources, based on ecosystem-based management. The initiative aims to develop tools for assessing risks and uncertainty in a changing world, which should include cumulative impacts.

In **Canada**, the Eastern Scotian Shelf Integrated Ocean Management Plan recognizes the need to "seriously address the cumulative, additive and synergistic effects" resulting from temporal and spatial use overlaps, but no actions or mechanisms to do this are contained in the plan (Fisheries and Oceans Canada 2007). At the provincial level, in Nova Scotia for example, cumulative impacts are considered in the EIA process and approval process for MRE projects, overseen by the Department of Environment. In the **United States**, because there is no national MSP system, cumulative impacts have not been addressed on a national scale. However, regional MSP initiatives, such as those led by RPBs and states, do address the importance of investigating cumulative impacts. In Massachusetts, for example, analysis has been conducted to assess the cumulative impacts of human uses by using spatial modeling efforts developed by the National Center for Ecological Analysis and Synthesis.[17] In Oregon, the plan does require an analysis of cumulative effects, which includes consideration of the effects of existing and future human activities and the regional effects of global climate change.[18] It should also be noted

17. *SeaPlan "Cumulative Impacts" http://www.seaplan.org/blog/project/cumulative-impacts/, accessed 20 August 2015.*
18. *http://www.oregon.gov/LCD/docs/rulemaking/tspac/Part_5_FINAL_10082013.pdf*

that all federal actions are subject to the National Environmental Policy Act (NEPA) and subsequent analysis, which does take cumulative effects into account. Overall, analysis of the cumulative impacts of MRE in the United States is limited, in part due to a lack of MRE infrastructure to serve as a base to study individual impacts.

8.5 DEALING WITH CONFLICTS IN MARINE SPATIAL PLANNING

The over-arching aim of MSP is to provide for the sustainable and efficient use of marine spaces by maximizing coexistence and minimizing conflicts. Traditionally, conflicts are dealt with on a case-by-case basis and if a compromise cannot be reached, in the worst-case scenario, the situation may lead to legal proceedings. Because MSP is a participatory process that seeks to involve all marine users and interest groups, the aim is to avoid conflict if possible or try to prevent it from escalating to insurmountable proportions. In the **United Kingdom**, conflicts between sectors are known to occur, but the process of marine planning aims to work through conflict and maintain stakeholder engagement throughout the process. In the draft South Marine Plans the MMO underwent an "Options" process, which saw the development of low, medium, and high strength policies for each sector. These policies were then compatibility tested and three different plan options were constructed: a flexible option (mainly low and medium strength policies), a balanced option (using as many high strength policies as possible), and a prescriptive option (high strength policies for key sectors/topics as identified through evidence gathering). The options report fully describes this process (MMO 2015). The result of the consultation meant that the MMO ended up with a combination of the balanced and prescriptive draft plan.

Elsewhere in the EU, the general trend is to deal with conflict situations on a case-by-case basis or avoid siting projects in areas where conflict with other marine uses is likely to occur. In **Spain**, because there is no national MSP framework conflicts are dealt with on a case-by-case basis. In the past this has tended to center on economic compensation to those most affected; for example, financial compensation to fishermen who lost access to their fishing grounds as a result of MRE development. In **Ireland**, conflicts are also dealt with on a case-by-case basis and in relation to MRE early engagement with those in the fishing industry secured an acceptable outcome for all parties when planning the AMETS on the west coast. As part of the MSP developed for **Portugal**, general and sector-specific management guidelines have been produced to guide and support activities in the territorial sea and contiguous zone and ensure compatibility between different marine users and increase synergistic activities. In **Sweden**, there are conflicts between offshore wind and other sectors, in particular (but not exclusively) nature conservation and defense. One of the aims of the MSP process is to deal with the conflicts and come up with possible alternatives for solutions of the conflicts applying a holistic and cross-sectoral perspective. Also, the MSP legislation gives some guidance on how to prioritize between different interests and objectives. The three integrated management plans developed for the marine waters of **Norway** each detail the specific sectoral interactions and conflicts. With respect to offshore wind in the North Sea plan area, there will be spatial overlaps with maritime transport activities, some petroleum exploration activities, and fishing, which could lead to conflict if not mitigated against. The plan suggests suitable mitigation measures such as amending shipping lanes and removing certain navigation aids where there could be conflicts with shipping; reducing the size of the area for offshore wind development where it could overlap with petroleum exploration activities; and early engagement with fisheries representatives so as to avoid important fishery grounds (Norwegian Ministry of the Environment 2013). Closer to the coast and within local spatial planning areas, there are conflicts among several sectors, including fishing and aquaculture (e.g., Narvik), platforms and vessels, and areas for conservation, landscape appreciation and recreation (e.g. Masfjorden, Rossfjorden/Lyngdal), as well as decommissioning of oil platforms, and fish spawning grounds (Vindafjord).

Fisheries is the sector most expected to conflict with MRE development in **Japan**. As a result developers meet frequently with those from the fisheries sector. There is no structured mechanism to do this and no formalized MSP systems. Marine renewable energy developers also meet with other maritime sector representatives. The process of communicating with other sectors will become more effective as experience accumulates. In **China**, almost 30 marine uses have been identified and one of the main purposes of MFZ is to allocate the most suitable sea areas for specific activities and thus avoid conflicts. In areas designated as an "agricultural and fishing zone" no industrial development involving marine reclamation can take place. Similarly in a "port shipment zone" no activities that would adversely impact upon shipping can take place in that zone. When applying to use an area of sea space, an EIA and justification for that use is required so that it can be demonstrated that the new use conforms with the requirements of the MFZ system.

In **South Africa**, the development of an integrated approach to ocean governance has been put forward by the government. This will include management plans for ocean areas, environmental variables, conflict scenarios, and trade-offs (Government of the Republic of South Africa 2014). One of the three focus areas is MSP and there is an associated target of delivering a national MSP framework by December 2015, which will be accompanied by a regional framework and more detailed small-scale marine spatial plans to enable the transition to a sustainable ocean economy. While the new approach to oceans governance does not include a conflict resolution mechanism, the associated Oceans Secretariat provides a means of resolving conflicts and finding trade-offs so as to unlock the ocean economy of South Africa. The cross-sectoral secretariat will also be able to facilitate discussions between departments when conflicts arise between permitting bodies. Design of MSP will incorporate identification of existing conflict zones and use this information in zoning future ocean activities and uses. In **Nigeria**, the conflicts that have arisen to date are related to the overlapping mandates of various government departments and agencies rather than relating to specific spatial areas.

In **New Zealand** there are already conflicts between different marine users. The Environmental Protection Authority has recently declined several high-profile applications where marine mining, environmental protection, and aquaculture activity came into conflict; e.g., Chatham Rock Phosphate Limited were refused a marine consent to mine phosphorite nodules in Chatham rise becauses it would have adverse environmental effects on benthic communities and potentially existing aquaculture operations in the area[19]. Three-quarters of all New Zealanders live within 10 km of the coast and Māori connections with the sea permeate many aspects of Māori life (cultural, spiritual, practical, and economic). The Māori have specific rights as a partner to the Treaty of Waitangi. There is growing conflict between the multiple economic, cultural, spiritual, and recreational uses of the marine environment, which are beginning to impede development of the marine economy, and there is increasing societal concern that the country's unique and diverse marine biota and the general health of the seas are at risk. To date consenting processes have been based on specific activities rather than being MSP-based, which could increase the possibility of conflict. The Sustainable Seas initiative will look at frameworks to assist the Māori and stakeholders to navigate conflicting uses, including trade-offs, mitigation measures, and negotiated accommodations (Ministry of Business, Innovation and Employment 2015).

In **Canada**, in the province of Nova Scotia, conflicts are dealt with on an ad hoc basis where those directly involved are encouraged to work out a compromise directly. Marine users are encouraged to proactively address concerns and establish working arrangements that reduce conflicts. In the **United States**, a number of conflicts have been encountered during existing MSP processes. Often, these have arisen when incumbent ocean users or agencies perceive risks to their interests as a result of proposed new uses. While each situation has had unique aspects, in general these have been resolved successfully through negotiation among affected stakeholders and the relevant state or federal authorities. The process to create the BOEM Wind Energy Areas (WEAs) was also not without conflict. The WEAs that were initially proposed for Maryland and Rhode Island/ Massachusetts intersected with shipping lanes and the Rhode Island/ Massachusetts WEA included areas critical to fishing interests. Each WEA was altered to accommodate these existing uses through active stakeholder participation and negotiation. Interestingly, and in contrast to other places around the world, several MSP processes in the United States have conflict prevention or resolution processes explicitly delineated in their enabling legislation, regulation, or policies. The National Ocean Policy (NOP) under which the RPBs are established states that all RPB and NOP efforts more broadly fall under and do not supplant or alter in any way existing authorities related to ocean use or regulation. In Washington State, the data identified areas meeting basic feasibility requirements for ocean energy that, if developed, could create conflict with existing uses. The suitability layer was incorporated into a state-run GIS tool available on the State's new MSP website, with a built-in user interface, making all data layers, including those that identify suitable locations for energy, fishing effort, marine protection, etc., accessible to planners, stakeholders, and the public (Van Cleve and Geerlofs 2013).[20] The Massachusetts Ocean Plan (Commonwealth of Massachusetts 2015) enables the creation of Renewable Energy Areas to allow for the development of commercial and community-scale wind energy facilities as well as wave and tidal energy facilities. Based on the presence of a suitable wind resource and water depth and the minimal conflicts with other uses and sensitive resources, two WEAs were designated within state waters (separate from the BOEM-designated WEAs on the Outer Continental Shelf) for commercial-scale offshore wind energy facilities.

8.6 ALLOCATED ZONES AND EXCLUSION ZONES FOR MARINE RENEWABLE ENERGY DEVELOPMENT

Some countries have allocated specific zones for definitive marine uses (Table 8.5). While this is not the function of MSP, ocean zoning is one method that can be used for implementing the objectives of a marine spatial plan. In certain countries, such as Germany and Belgium, offshore wind development in particular has acted as a driver for the implementation of MSP and dedicated zones have been designated for the expansion of that activity in future.

The use of ocean zoning for specific activities varies worldwide. As one of the most mature maritime industries, shipping has internationally recognized transit passages and shipping lanes that are often regarded as sacrosanct. On occasion and in very specific circumstances these can be amended to accommodate other marine uses. This has already happened in the English Channel as a result of safety concerns resulting from the construction and operation of the Wave Hub offshore testing facility in the waters off Cornwall where a recognized Traffic Separation Scheme operates off Land's End, between the UK mainland and the Isles of Scilly on the southwest coast of England. The UK regulatory agencies in association with the International Maritime Organization amended the Traffic Separation Scheme, moving it 12 nautical miles to the north of the current boundaries and also amending the Inshore Traffic Zone to the east (IMO 2008). Other reasons for exclusion zones are due to health and safety concerns. The European Boating Association views the total exclusion of small craft from offshore wind farms as "unnecessary, impracticable and disproportionate" because it could force such craft into busy commercial shipping lanes, thereby increasing the risk of collision (EBA 2013). The German government has also recognized the negative implications of imposing safety zones on small craft (under 24 m) and has exempted them from such zones in certain situations.[21]

8.7 TOOLS USED TO IMPLEMENT MARINE SPATIAL PLANNING

There are many ways in which MSP can be implemented. MSP does not replace the need for sectoral management plans but rather provides a framework for these to fit into a nested approach. Rules, regulations, protocols, guidelines, technology, zoning, technical measures, and mapping are all tools that can be used to implement MSP and management. Responses to the survey focused almost entirely on the use of technology to implement MSP, specifically the use of GIS-based portals and databases. Some of the tools listed in Table 8.6 cannot implement MSP directly but could be used in future to assist in that process.

8.8 LIMITATIONS TO THE IMPLEMENTATION OF MARINE SPATIAL PLANNING

Data and resources were the two main factors identified as limiting the implementation of MSP. In a number of countries political will was also listed as a limitation. Other respondents were of the opinion that the system in place nationally while not termed MSP actually fulfilled the same purposes. Most frequently this took the format of integrated coastal plans that apply to varying extents in the coastal zone and parts of marine waters. Elsewhere the terrestrial planning systems and associated policies allow for the creation of development plans that can take nearshore areas into account. In the EU, the obligation on Member States to have a MSP now as a result of the new Directive could cre-

20. *http://www.msp.wa.gov/*

21. Currently this is limited to one operational wind farm in the Baltic Sea, no others are yet legally classified as operational. *https://www.elwis.de/BfS/bfs_start.php?target=3&source=1&aboexport=abo&db_id=87456*

Table 8.5. Zones and prohibitions for MRE.

Country	"Zones"	Prohibitions
United Kingdom	The Crown of State have held six offshore wind leasing rounds (including extensions, Scotland, and Northern Ireland). Six seabed areas have also been leased for wave and tidal demonstration zones, and several other seabed leases have been issued for individual projects.	No absolute prohibitions but may be additional consenting requirements in designated sites and/or military areas.
Spain	SEA for offshore wind indicated that only 3% of the areas considered were suitable for development with 62% mapped as unsuitable (Ministerio de Industria, Energía y Turismo, 2009).	Unsuitable areas were designated as such because significant environmental effects were expected or there were conflicts with other priority marine uses.
Portugal	Existing test site areas that have expanded.	None.
Sweden	Only test sites exist.	Certain marine reserves.
Norway	Zones are allocated for offshore wind but not ocean energy.	None known.
Ireland	Test sites exist, an SEA for marine renewables has been conducted, no leasing rounds as yet.	No absolute prohibitions but may be additional consenting requirements in certain locations.
Japan	No zones, small demonstration sites	Difficult to develop in military areas and nature reserves.
China	Marine functional zoning prescribes uses in specific zones.	Uses can only occur within specifically allocated zones.
South Africa	None at this time.	Development prohibited in certain protected areas along the coast.
Nigeria	None at this time	No allocated or restricted zones exist at this time.
New Zealand	Only a limited number of projects at this time, no specific zones.	Some restrictions in EEZ due to sensitive ecosystems, local economic activities and Māori interests.
Nova Scotia, Canada	Areas of Marine Renewable Energy Priority (AMREP) are considered as planning areas, and only Marine Renewable Electricity Areas (MREAs) will be allowed to develop.	Other uses will not be allowed in the designated AMREP or MREA.
United States	Certain States have MRE sites earmarked for development but no national zoning process exists.	Activities in National Marine Sanctuaries that would alter the seabed or subsoil or potentially effect environmental conditions within the sanctuary are prohibited. Also military areas, shipping and transport lanes etc. Can also be state level.

ate problems in countries that already have a mature marine planning system in place. To allay this concern, the EU Directive emphasizes that any MSP created for the purposes of the Directive should not contain new sectoral targets or objectives. A summary of the limitations to implementing MSP within each of the thirteen countries are provided in Table 8.7.

8.9 PUBLIC INVOLVEMENT IN MARINE SPATIAL PLANNING

Stakeholder consultation has been an important part of developing marine plans in the **United Kingdom**. The MMO's marine planning team has engaged with the public through workshops and public consultation throughout the planning process. For each plan area, a Statement of Public Participation describing how and when the MMO would provide people with opportunities to get involved in the preparation of marine plans for areas in which they live, work, or have an interest and what they then do with the views and opinions

Table 8.6. Tools used to implement MSP.

Country	Tools	*Link*
United Kingdom	Marine Information System (MIS) [MMO] Marine Planning Portal [MMO] Marine Resource System (MaRS) Welsh Government Marine Planning Portal	*http://mis.marinemanagement.org.uk/* *https://planningportal.marinemanagement.org.uk/* *http://www.thecrownestate.co.uk/mars-portal-notice/* *http://lle.gov.wales/apps/marineportal/*
Spain	GIS-based tools	*Unavailable*
Portugal	Dedicated GIS for MSP	*Unavailable*
Ireland	Ireland's Marine Atlas INFOMAR Ocean Energy Ireland portal Marine Irish Digital Atlas	*http://atlas.marine.ie/* *http://www.infomar.ie/* *http://oceanenergyireland.ie/* *http://mida.ucc.ie/*
Sweden	Variety of regulatory and technical tools	
Norway	Mareano (bathymetric maps) State of the Environment atlas Barents Sea Advanced Spatial Planning Tool Efficiensea Interreg Project	*http://www.mareano.no/* *http://www.environment.no/maps/* *Unavailable* *http://mrfylke.no/content/search?SearchText=efficiensea*
Japan	Open access marine cadastre	
China	Dedicated GIS system for marine functional zones with complete database	
South Africa	Operation Phakisa will culminate in the development of specific GIS for MSP	
Nigeria	Tools used depend on the responsible authority and the sector concerned	
New Zealand	Tools expected to be developed under the Sustainable Seas initiative	*http://www.sustainableseaschallenge.co.nz/*
Canada	No specific tools in place yet; new legislation for Nova Scotia may see the development of a MRE-specific GIS	
United States	Regulatory and technical tools exist, e.g., Northeast Regional Ocean Council and Mid-Atlantic Regional Council on the Ocean (MARCO) data portals Marine Cadastre Marine Map - Oregon is using Decision Support Tools to guide planning and siting; e.g., Marine Map	*http://marinecadastre.gov/* *http://www.seasketch.org/home.html*

Table 8.7. Limitations to implementing MSP.

Country	Limitations Cited by Respondents
United Kingdom	Comprehending and communicating the ever-changing nature of these environments. Insufficient data in certain locations. Uncertainty surrounding impacts of climate change.
Spain	Lack of coordination between the administrative entities with a marine remit at national and local levels. Unclear definition of role between the responsible authorities.
Portugal	Lack of real data for the Portuguese marine space.
Sweden	Lack of a common baseline for countries sharing marine areas. No cross-border maps of available or theoretical marine energy resource or identifying suitable sites. Methodology to assess and address cumulative effects of offshore wind is needed. More information needed on green infrastructure and the marine ecological values. Lack of consideration of the marine in local plans so possible a lack of MSP expertise.
Norway	Significant resource challenges for mapping, analyses and pan implementation and review. Transboundary issues as a non-EU country. Municipalities need more capacity for planning and data at local levels.
Ireland	Need to decide on the most appropriate design for marine planning Resources also needed.
Japan	Limited human and financial resources for marine as it is low priority area.
China	Insufficient inshore maritime space. Increasing demands for sea area uses in each province. Need to integrate land and sea planning systems. Mechanisms for conflict resolution. Methodologies to evaluate the operation of marine functional zoning. Greater stakeholder involvement in zoning decisions.
South Africa	Limited human capital and funding are the most significant limitations. Marine resources and space allocation is not a priority area of concern. Little demand for sea space and steep shelf gradient could limit future prospect for MRE development
Nigeria	Many institutions and organizations collect and retain different marine data and no mechanism is in place nationally to integrate existing data. No strategic approach to data collection due to lack of financial resources.
New Zealand	Larger industry players would benefit from having a consistent message. Existing regional planning system works well.
Canada	Need to more effectively integrate land and sea planning. Existing regional planning system works well. No singular coordinating body driving MSP development/implementation due to limited resources among government departments and agencies.
United States	Experience and implementation is limited to the state level or specific sectors due to legal and political limitations.

expressed, must be produced. Such engagement should make the plans as widely beneficial as possible and reduce the potential for conflicts. In **Northern Ireland**, for example, the Marine Plan Team published a "Statement of Public Participation" in June 2012 (DOENI 2012), which was subsequently reviewed and updated in May 2013 (DOENI 2013). In **Spain**, the public are consulted on marine developments as part of the formal EIA process, but because no MSP system is in place nationally it is not known if and how the public would be involved. In **Portugal**, a number of public information sessions were held for the public and for different maritime sectors during the development of the marine spatial plans for Portuguese marine waters. These sessions were held regularly and acted as a mechanism for updating stakeholders about current progress as well as a forum to gain input on particular components of the plan. The final version of the marine spatial plan was open for public consultation for a period of three months.

In **Sweden**, the legislation governing MSP stipulates broad consultation of the plan proposals before the proposals are submitted to the government. Because the process is in its initial phase the general public have not yet been involved in it. The public will be involved in the regional and municipal processes. Sectoral interest groups were consulted in the preparatory phase. In **Norway**, to achieve transparency, all reports and other documents were made available through the Internet, and stakeholders are invited to comment at steps in the process. This will continue into the future as the plans continue to be implemented. Meetings can also be hosted by industry representatives and nongovernmental organizations (NGOs). At the local level, for inshore waters, the Planning and Building Act contains rules for public participation including public hearings, contributions, and meetings. In **Ireland**, the Enabler's Task Force on MSP highlighted the need for any future MSP framework developed in Ireland to be participatory and involve multiple stakeholders (Enabler's Task Force 2015).

In **Japan**, MRE developers host many information meetings and workshops for all stakeholders. It can be challenging to incorporate the opinions of those from the fisheries sectors, so developers often hold separate meetings with that user group. In **China,** as part of the MFZ process, members of public are consulted and can give their opinions. Where zoning plans have been finalized and are operational, the public can access the plans and supporting documentation on the associated information management system, which is publicly accessible via the Internet. In **South Africa**, where MSP is still under development it is not yet clear how the public will be involved in the process. In the coastal zone all activities that require an EIA involve public participation as part of that process. **Nigeria** does not yet have MSP in place so the role of the public and how their views will be incorporated is unknown at this time. **New Zealand** has a clear guide for how to participate in the planning process;[22] generally though this is not exactly MSP. The planning approval process in New Zealand is highly participatory. The Environmental Protection Authority and the Resource Management Act have an open process and solicit public views. In the NZCPS, one of the objectives (Objective 6) is to enable people and communities to provide for their social, economic, and cultural wellbeing and their health and safety (New Zealand Government 2010). The associated implementation plan for the NZCPS has a dedicated "engagement" stream that is targeted at district and regional councils, so they are well informed about the requirements and statutory obligations of the policy and are supported to implement its policies (Department of Conservation 2011). This is supported by a range of specific actions designed to engage with different stakeholder groups, both regulatory and non-regulatory.

In Nova Scotia, **Canada**, there is no MSP in place at this time, but the regulators are beginning to develop the process for designating sites for MRE development. To date there has been a long yet somewhat indirect discussion of MSP for MRE. Starting in 2008 through consultation for a SEA in the Bay of Fundy, Nova Scotia has looked at getting public input on how the development of MRE should be managed from a spatial conflict perspective. This exercise was completed again in 2014 for the Bay of Fundy and the Bras d'Or Lakes. In 2011, there was also consultation on proposed MRE legislation that briefly touched on associated spatial issues. The consultation to date however has not focused on MSP, but rather the broad issues around MRE. Future designation of MREAs will be guided by consultation with the public.

22. http://www.environmentguide.org.nz/rma/planning-documents-and-processes/participating-in-the-plan-change-process/

In the **United States**, engagement with public stakeholders has been incorporated at multiple points in MSP processes to date. Consultation with various stakeholders and between the lead agency and other relevant government authorities is performed at multiple stages of the process. With respect to planning for individual projects, stakeholder consultation starts at the very beginning of the project development, and public comment periods are incorporated at multiple stages in the regulatory process. In order to receive a FERC license or BOEM lease, a series of mandatory consultations are performed, usually in conjunction with the NEPA analysis (WavEC 2015). At the state level, in Washington State, stakeholders representing a wide range of ocean interests on four, county-based Marine Resources Committees have driven MSP efforts (Van Cleve and Geerlofs 2013). The Massachusetts Ocean Management Plan was the product of over 18 months of public process and was the product of "18 public meetings, 90 stakeholder consultations, and countless hours on the part of private citizens and state officials alike" (Johnson 2014). In the Rhode Island SAMP, the Coastal Resources Management Council applied guiding principles of transparency, stakeholder involvement, regard for existing ocean users, incorporation of best available science, and principles of adaptive management to the plan's development. These principles were applied within a framework that allowed for technical advisory committee review and public comment on each draft chapter as it was prepared. A series of 18 stakeholder meetings occurred between October 2008 and January 2011, with participation by representatives from fisheries groups, conservation organizations, marine trades and unions, tribal agencies, historical societies, utilities, recreation groups, tourism councils, chambers of commerce, and local governments.[23] Oregon used a public involvement plan for its update. After a complex and lengthy stakeholder participation process, this update was completed in January 2013 (Van Cleve and Geerlofs 2013).

8.10 CONCLUSIONS

Because MSP is a relatively new management approach and MRE is a comparatively new use of the marine environment, it is difficult to draw firm conclusions about the extent to which one is influencing the other at this time. Not all countries have a formalized MSP system, but many have equivalent approaches such as regional plans or coastal management plans. There is a strong desire for land and sea planning systems to be more coordinated and MSP is one approach to facilitate this. To date there has been limited consideration of MRE in MSP with few practical examples. In certain countries there is little demand for marine space, so MSP is low on the political agenda. The scientific data needed to support planning of marine and coastal uses needs strengthening and MRE data appear to be limited to the availability of the physical resource. Cumulative impacts remain problematic with no agreed-upon methodology for how to address them. The same can be said of conflicts with other marine users that appear to be dealt with on a case-by-case basis. It is rare currently to have dedicated zones for MRE and restrictions to siting development are common in areas of high conservation value or where there are pre-existing military uses. Limitations to the implementation of MSP reflect technical, political, and financial aspects that can be barriers in a number of different countries. What is clear from all of the survey respondents is that there is a strong desire for more integrated planning and high hopes that MSP will solve some of the existing issues associated with development at sea. This chapter reveals that MSP is perhaps not as prominent as it should be at this time for MRE. Certainty and clarity in the regulatory framework is necessary for investors and any future changes in the planning system, on land or at sea, will affect development decisions. There is a desire among all actors (developers, regulators, and stakeholders) for examples of good practices that can be applied in their areas. Annex IV can contribute to this through the dissemination of relevant information and examples.

23. *http://seagrant.gso.uri.edu/oceansamp/stakeholders.html#stakeholder*

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QUESTIONNAIRE CIRCULATED TO ANNEX IV PARTICIPANT COUNTRY REPRESENTATIVES

Question 1

Does a formal Maritime Spatial Planning process exist in your country? If yes, please describe this process with links to key documents and legislation.

If no formal MSP system yet exists in your country please describe the current planning system that applies to marine developments, in this question and the following questions. This could include processes that operate in parallel, those that incorporate adaptive management, participatory approaches etc.

Question 2

To what extent does the Maritime Spatial Planning process in place incorporate Marine Renewable Energy as a specific sector? Is this the same for offshore wind, wave and tidal energy?

Question 3

How were the requirements of the Marine Renewable Energy sector taken into account in the development of the Maritime Spatial Planning process? For example, did the findings of a Strategic Environmental Assessment [or equivalent] of marine renewables inform the process, were there meetings with key industry players or trade associations, etc.?

Question 4

How has scientific information been incorporated into Maritime Spatial Planning? In your answer please indicate the type of scientific information included and whether this was derived from 'real-life' data, specially developed models, data from other industries etc.

Question 5

How have cumulative impacts been addressed in your national Maritime Spatial Planning system?

Question 6

Have there been any conflicts between different marine sectors / users such as fisheries, conservation, recreation etc.? How does your marine planning system address this issue? Please give examples, where possible.

Question 7

Are there any specific marine ± coastal areas where development of Marine Renewable Energy projects are absolutely prohibited? This could include, for example, military training areas, Marine Protected Areas, fishing zones etc.

Question 8

What tools are used to implement Maritime Spatial Planning system in your country? Tools could include a specific Geographic Information System (GIS), zoning for specific uses, specific regulations etc.

Question 9

In your opinion, what is the key limiting factor to implementation of Maritime Spatial Planning in your country? This could include, for example, limited marine data availability, limited human and/or financial resources, lack of priority attributed to marine development etc.

Question 10

How have the public been involved in Maritime Spatial Planning?

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9.0

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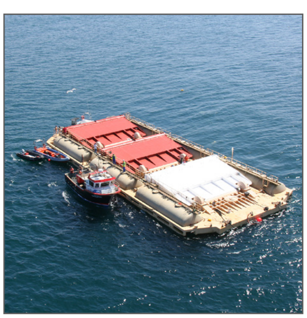
Case Studies that Examine Siting and Permitting/ Consenting of Marine Renewable Energy Devices



The consenting process, including the environmental impact assessment of ocean energy projects, is still regarded as a challenge to marine renewable energy scale-up to create a cost-competitive viable MRE industry. Specifically, uncertainty about the appropriate application of environmental legislation, which can prolong the consenting processes (adding cost and delay) is a key focus area. Currently the environmental effects and impacts of MRE devices on the marine environment, and vice versa, are significant areas of uncertainty. Furthermore, the scarcity of data on the environmental interactions of new technologies often means they are characterized as a threat, requiring extensive supporting environmental information, the collection of which can be costly and time consuming.

Data and information about environmental effects are being derived from time-limited single device demonstrations at sea, usually in test centers, or from specific aspects of the consenting process, namely studies to support EIA. The latter varies considerably in scope and intensity among countries meaning that little integration can be achieved across the experiences to date. Different methodologies and time frames are used and this reduces the ability to draw firm conclusions or trends from environmental impact information, which therefore limits the ability to address this issue on a wide scale. However, some lessons can be learned from previous projects about better practices and these may help pave the way for the development of future ocean energy farm development.

The main objective of this chapter is to identify the primary barriers to the consenting of ocean energy projects that are limiting effective siting and efforts to support sector development. Case studies of licensing experiences are presented and further discussed to compare them by region, to identify data gaps, and to provide recommendations for better practices. A case study from each technology (wave and tidal) and site type (designated test center or technology test site) has been selected for description and analysis.

9.1 APPROACH AND INFORMATION SOURCES

A template for the description of case studies was developed to be sent to people directly involved with the development of selected projects. This template has been filled in for four case studies: WaveRoller technology, installed in Portugal; the TidGen® Power System, installed in the United States; SeaGen technology, installed in Northern Ireland; and BIMEP, a designated test site in the Basque Country, Spain. An effort was made to include some of the most evolved technologies in terms of testing at sea, representing several countries to draw a broader picture of the status of the licensing of such projects. The information gathered here has been directly reviewed by the technology developers and the test site managers.

9.2 WAVEROLLER – PORTUGAL

The WaveRoller technology, developed by the Finnish company AW-Energy Ltd, uses the well-known surge phenomenon to convert wave energy into power. Beginning in 2004, a prototype was initially tested in Orkney (by EMEC) and Ecuador, but in 2006 the Portuguese coast was identified as the most suitable location to demonstrate the power plant. Prototype sea trials took place in 2007 and 2008 and grid-connected demonstration project sea trials in 2012–2014. The test site, located off Peniche (on the central coast of Portugal), involved collaboration among local authorities, scientific entities, and a utility company. A new version of the device, with an installed capacity of 350 kW, is now being prepared to be installed and tested at the same location in 2016, and there are plans to install the first farm after testing is completed.

9.2.1 LICENSING REQUIREMENTS

9.2.1.1 PRE-CONSENT REQUIREMENTS

In Portugal, the required consents have been adapted to better suit wave energy developments. Under this process, the WaveRoller promoter had to submit a pre-application form identifying the project characteristics and an annex specifying the project location and the site characteristics. The latter included characteristics related to navigation, fisheries, leisure areas, water depth and wave climate, water circulation patterns, weather data (wind and storm data), emergency plans, and land infrastructure associated with the project. The environmental licensing was managed by the regional authority (Coordination Committee on Regional Development) for the area in which the project was to be located, and an EIA was carried out in 2011. A conditionally favorable Environmental Impact Study (EIS) was issued with several conditions to be fulfilled before, during, and after device deployment. The most relevant conditions were the development and implementation of two monitoring plans: one to follow the effects on marine mammals and the other to follow the benthic communities within and around the site area.

9.2.1.2
POST-CONSENT REQUIREMENTS

Two monitoring plans with the following objectives were required for approval by the authorities: 1) monitoring of the benthos growth on the device moorings and flap and effects of the project on the benthos communities in and around the device location; and 2) monitoring of the effects of the project on the local marine mammal populations. In addition to the legal requested monitoring activities, the WaveRoller developers decided to carry out a monitoring program for the analysis of project effects on the underwater acoustic conditions, particularly on sensitive species such as marine mammals. The work consisted of acquiring acoustic data for ambient noise characterization and during device operation for device noise characterization.

9.2.2
ENVIRONMENTAL MONITORING AND KEY FINDINGS

9.2.2.1
MARINE COMMUNITIES

The overall results showed that soft-bottom benthic communities were characterized by low biodiversity and abundance, typical of sandy areas with strong wave regimes. Community composition was mostly crustaceans and polychaetes, and no relevant differences were encountered between sampling dates, even including the post-deployment campaign results.

The results obtained for the hard-bottom analysis were somewhat different between baseline and post-deployment campaigns. During the baseline campaign, rocky substrate was largely colonized by *Sabellaria alveolata* biogenic reef; during the post-deployment survey, soft sediment covered most of the area, including rocky outcrops, and consequently Sabellaria reefs were scarce, appeared to be degraded, or were covered by soft sediment. Although the results show differences in hard-substrate communities between the baseline and post-deployment campaigns, the differences cannot be directly attributed to deployment of the WaveRoller device because of its high extension level, short period of time it has been in the location, and associated project-reduced dimensions (footprint). These differences in the hard-bottom communities are most likely related to the strong hydrodynamic characteristics of the area. However, monitoring is needed to confirm this conclusion in the future, when the device deployment is longer than it was during testing deployments.

9.2.2.2
MARINE MAMMALS

Data collected during both campaigns appear to be in accordance with previous observations, carried out between 2007 and 2014, regarding the occurrence of common dolphins in the region. This seems to be the most common species of cetaceans in the region; it is also the most common marine mammal species sighted off Portugal mainland. Marine mammal species appear to be preferentially using areas far from the device location (to the north and south limits of the study area), because no sightings have been registered between these two limits during both campaigns. Furthermore, the site is located in shallow waters with depths that are too shallow to be used by the local populations. After acquiring these results the authorities approved the discontinuance of the marine mammals monitoring activities, because no impacts on this group of species have been detected.

9.2.2.3
ACOUSTICS SURVEY METHODOLOGY AND RESULTS

The results of the acoustic survey indicate that more measurements at longer distances from the device are needed to assess the distance at which the SPL (sound pressure level) decays to baseline values. A positive and strong correlation exists between the SPL and the WaveRoller power production and wave height at the nearest sampling point from the device (220 m). Impacts of the WaveRoller noise are not expected on odontocete cetaceans because they are not able to hear the sound produced by the device. Behavioral responses might be identified in low- and mid-frequency cetaceans if they swim near the WaveRoller, which is unlikely because of the shallow depths in which the WaveRoller devices are to be installed. Injury impacts are not expected to occur.

9.2.3
PRIMARY BARRIERS TO CONSENTING

Consultation with several statutory stakeholders revealed some concerns about protected species using the site on land and habitat destruction related to the substation installation on the dunes. Thus mitigation measures were implemented by the developer to recover the site around the substation and to prevent adverse events identified by the authorities (e.g., oil leaks from the substation). The project has been accepted for installation with the monitoring recommendations described above. Although the licensing time was short, compared to other wave energy developments in Portugal, the time involved to receive consent was mainly a reflection of the lack of knowledge about how to license this kind of new project and work successfully within the existing bureaucracy to do so.

9.2.4
LESSONS LEARNED AND RECOMMENDATIONS

Developer consultation with statutory consultees, local stakeholder groups, and the public before and during wave energy developments was crucial to overcoming barriers to project development. From the administrative perspective, consultation before delivery of official documents by the developer for approval (e.g., before submitting monitoring plans) has been shown to be very important in speeding up the consenting process. Informal consultation and effective involvement of key stakeholders were also very important, not only to promoting public awareness of developments but also to understanding and considering community concerns during project installation and deployment. These practices enable stakeholders to trust developers and may avoid further problems of public acceptance, while also fostering project success.

9.3
OCEAN RENEWABLE POWER COMPANY – UNITED STATES

Ocean Renewable Power Company, LLC, and its wholly owned subsidiary ORPC Maine, LLC (collectively, ORPC), develop MHK power systems and eco-conscious projects that harness the power of ocean and river currents to create clean, predictable renewable energy. In 2012, ORPC built and operated the Cobscook Bay Tidal Energy Project, the first revenue-generating, grid-connected tidal energy project in North America. It became the first ocean energy project to deliver power to a utility grid anywhere in the Americas. The purpose of the project was to evaluate the potential for a new source of clean, renewable energy generation using tidal energy resources in Cobscook Bay, Maine. The project site is located off the coast of Eastport and Lubec, Maine. This was the first grid-connected installation of ORPC's TidGen® Power System.

9.3.1
LICENSING REQUIREMENTS

9.3.1.1
PRE-CONSENT REQUIREMENTS

In the United States, the FERC regulates marine hydrokinetic projects through a licensing process, which begins with a preliminary permit and is followed by a multi-staged pilot project license application. ORPC obtained a preliminary permit for the project area in Cobscook Bay from FERC on July 23, 2007, and FERC issued a successive preliminary permit on January 13, 2011. Feasibility studies, including environmental surveys, and pre-filing consultation were conducted. ORPC filed a draft pilot project license application with FERC on July 24, 2009, and subsequently, the final pilot project license application in September 2011. The final pilot project license application included environmental monitoring plans and environmental assessment. ORPC received a pilot project license for the Cobscook Bay Tidal Energy Project from FERC (No. P-12711-005) on February 27, 2012, following approval of its installation plans by FERC's Division of Dam Safety and Inspection.

9.3.1.2
POST-CONSENT REQUIREMENTS

ORPC developed an Adaptive Management Plan as required by the FERC pilot project license. The Adaptive Management Plan is an integral part of ORPC's implementation of the Cobscook Bay Tidal Energy Project and provides a strategy for evaluating monitoring data and making informed, science-based decisions to modify monitoring as necessary. The Adaptive Management Plan, therefore, was designed to be modified within the project time line and acknowledges that elements such as key environmental uncertainties, applied studies, and institutional structure may evolve over time. The plan has worked well for the agencies, stakeholders, and ORPC as the project evolved from a concept to the first pilot installation and operation.

The following environmental monitoring plans were adopted as license articles or post-consent requirements in ORPC's FERC pilot project license. Results to date indicate significant achievements that contribute to our overall understanding of device interactions in Cobscook Bay (table 9.1).

Table 9.1 Monitoring plans developed for the Cobscook Bay project adopted as license articles or post-consent requirements.

Article 405.	Acoustic Monitoring Plan
Article 406.	Benthic and Biofouling Plan
Article 407.	Fisheries and Marine Life Interaction Plan
Article 409.	Hydraulic Monitoring Plan
Article 410.	Marine Mammal Monitoring Plan
Article 412.	Bird Monitoring Plan.

9.3.2 ENVIRONMENTAL MONITORING AND KEY FINDINGS

The implementation of the environmental monitoring plans was affected by two overriding challenges: the realities of working regularly in the marine environment (i.e., limited visibility, high velocity, deep water conditions with changeable weather at the surface) and the startup, conditioning, and maintenance issues associated with the new marine hydrokinetic technology and environmental monitoring instrumentation, especially the components that represented first of their kind applications. To overcome these challenges ORPC took the following approach to ensure consistency with the project's license: 1) data were collected in accordance with the approved environmental monitoring plans and Adaptive Management Plan and in conjunction with the installation of infrastructure and the operational status of the Tidal Generation Unit (TGU); and 2) where deficiencies in equipment and methodologies were identified, ORPC engaged technical advisors, consulting scientists, manufacturer representatives, and qualified in-house personnel to troubleshoot issues and develop improvement plans, as necessary. Fisheries studies and studies of the effects of noise from the devices were undertaken but showed no discernable effects at the level of the single devices tested. Key findings are that the ORPC Power Systems have "no known adverse impacts on the marine environment" after extensive third-party monitoring.

9.3.3 PRIMARY BARRIERS TO CONSENTING

The consenting process is lengthy and costly as is environmental monitoring. Yet federal and state regulatory agencies have shown a willingness to facilitate efforts to the extent possible.

The consenting was hindered by a lack of "best available science" to evaluate potential environmental effects from the turbine installation and operation. In addition, the number of federal and state agencies with jurisdiction over the project created a very complex and time-intensive consultation process.

A Memorandum of Understanding between FERC and the state of Maine greatly helped diminish the time and effort required to consult with state agencies by making the Maine Department of Environmental Protection the lead agency at the state level.

In addition, a collaborative approach between regulatory agencies, technical advisors, and ORPC to develop methodologies and technologies to assess environmental interaction led to the development of best available science that ultimately contributed to an adaptive management process that allowed for modifications to levels of monitoring based on data collected.

9.3.4 LESSONS LEARNED AND RECOMMENDATIONS

The Cobscook Bay Tidal Energy Project has demonstrated the value of installing full-scale tidal turbines and the knowledge base gain from doing so. Through collaborative efforts to develop methodologies and technologies to collect science-based data, an effective adaptive management process and team, and results that have indicated no observed negative effects on the marine environment, a roadmap and process for future projects has been established. ORPC has implemented the best practices developed from the Cobscook Bay Tidal Energy Project on other hydrokinetic projects in the United States and has demonstrated significant time and cost reduction as a result.

9.4 SEAGEN – UNITED KINGDOM

In July 2008, SeaGen, installed in the Strangford Lough Narrows, Northern Ireland, became the world's first commercial-scale tidal turbine to feed electricity into the national grid. The company behind this major accomplishment was MCT, a British tidal energy company based in Bristol, England. SeaGen works on the same principle as a windmill, except underwater, extracting energy with twin rotors each spanning 16 m in diameter to produce enough electricity to supply approximately 1500 homes. At the time, this 1.2 MW device could produce four times greater energy than any other tidal turbine. In February 2012, Siemens acquired MCT, which carried on running and developing SeaGen. Then in July 2015, Atlantis Resources acquired Marine Current Turbines Limited from Siemans AG. At this stage, the surface piercing tidal SeaGen system (SeaGen S) held the record for the longest running marine current turbine—operating for more than 5 years.

9.4.1 LICENSING REQUIREMENTS

9.4.1.1 PRE-CONSENT REQUIREMENTS

When MCT identified the Narrows of Strangford Lough as a potential site for deployment of the SeaGen tidal turbine in 2004, the Lough had already been designated a Special Protection Area (SPA) since 1998. SPA status presented a challenge to the regulator to protect Strangford Lough, which then became an EU-listed Special Area of Conservation (SAC) in 2008 because of its conservation features. In 2004, the placement of a tidal turbine in the Narrows of Strangford Lough required a Food and Environmental Protection Agency (FEPA) marine construction license from the Northern Ireland Environment and Heritage Service, now Northern Ireland Environment Agency. In 2005, MCT commissioned Royal Haskoning to conduct an EIA and that firm also provided an Environmental Statement (ES) that accompanied the application for the license that was granted to MCT in December 2005. The ES concluded that the potential impact of the SeaGen device on some features were uncertain, but that adverse impacts were unlikely. MCT's receipt of the FEPA license was based on an agreement that a comprehensive Environmental Monitoring Plan (EMP) would be established that not only covered the pre-installation, but the installation, operation, and decommissioning phases of the project. Data collection began in April 2005, before the installation of SeaGen.

9.4.1.2 POST-CONSENT REQUIREMENTS

Upon receiving consent for the installation of SeaGen, MCT established a £2 million EMP to closely monitor the environmental impact of SeaGen. Development of the EMP involved Queen's University Belfast and the SMRU at St Andrew's University and was managed by Royal Haskoning. The EMP used an adaptive management approach by providing ongoing monitoring of habitats, species, and the physical environment of Strangford Lough. This adaptive management approach was designed to detect, prevent, or minimize the environmental impacts attributed to the turbine throughout the different phases of the operation of SeaGen. The research program monitored four elements—marine mammals, seabirds, benthic ecology, and hydrodynamics—and was required to run for three years after the installation of SeaGen. Two groups were set up in 2006 to manage, scientifically review, and advise the EMP team: a small Science Group to provide advice on the detailed management of the EMP and a wider Liaison Group to whom Science Group progress was reported. Both groups met regularly and the results of the EMP were reported bi-annually; a final report was produced in January 2012.

9.4.2 ENVIRONMENTAL MONITORING AND KEY FINDINGS

9.4.2.1 MARINE MAMMALS

A very detailed and comprehensive study of marine mammals was carried out as part of the EMP. The data collected since 2004, encompassing before and during the installation and operation of SeaGen, have provided the marine energy industry and the scientific community with valuable detailed insights into marine mammal behavior in a high tidal environment and in the presence of a tidal device that previously were unknown. Three mammal species are resident in Strangford Lough: the harbor seal (*Phoca vitulina*) which are covered by the SAC, the grey seal (*Halichoerus grypus*), and harbor porpoise (*Phocoena phocoena*). Other marine mammals also frequent the Strangford Narrows, including basking sharks, dolphin species., and whale species. The EMP objectives were diverse and included carcass surveys, active acoustic monitoring, pile-based observations, seal telemetry to track individual harbor seals, acoustic monitoring of harbor porpoises in the narrows using Timing Porpoise Detectors, shore-based visual observations of marine mammals around SeaGen, measurement of operation noise, and aerial surveys and boat counts of seal population abundance and distribution.

These studies involved a range of spatial and temporal scales with some actions, such as seal telemetry, only carried out at one time during the operation, while other studies, such as active acoustic monitoring, were carried out at all times that SeaGen operated since 2008 (24/7).

The EMP results suggest that SeaGen had no major impact on harbor seals, grey seals, or harbor porpoises. The only minor disturbance was during the construction of SeaGen when some displacement of the harbor porpoises occurred near the structure, but once the installation was complete, the harbor porpoises returned to the narrows. A further observation was the suggestive small-scale changes in the local vicinity of the device during installation and operation: tagged seals continued to swim past SeaGen, only closer to the shoreline; and individual seals transited slightly less often during operation. Observations from the active acoustic monitoring results suggest that more movement was observed near the turbine during slack tide. But the modifications to mammal behavior were small, showing avoidance of the device with no significant effect on survival or fitness of these marine mammals.

9.4.2.2
SEA BIRDS

Numerous bird species either reside in or migrate through Strangford Lough and are one of the reasons why Strangford Lough was designated a SPA. The initial ES report identified eight bird species considered the most likely to be affected by the installation of the turbine because of their feeding behavior. Out of the eight species, anecdotal evidence suggests that terns, gannets, cormorants and shags are the main species feeding in the narrows. All of these birds either plunge or dive to catch fish; gannets dive to depths of 15 m. Monitoring of the number, distribution, and activity of the relevant bird species was carried out between April 2005 and March 2011 from a single vantage point on the shore opposite SeaGen. Results based on historical data and data collected from shore-based surveys conducted during the installation and operation of the tidal device suggest that SeaGen had little impact of ecological or conservation significance on the bird species investigated. Behavior changes noted in the vicinity of the turbine were not sufficient to detect a change in any of the diving bird populations. However, small-scale changes may be undetected and the long-term effects are unknown.

9.4.2.3
BENTHIC COMMUNITIES

The substrate in the Narrows of Strangford Lough is primarily tide-swept bedrock and boulders supporting a wide range of species, notably suspension-feeding species, including soft corals, sponges, bryozoans, hydroids, and sea anemones. The habitat is described as being rich in terms of biodiversity and production, but the major challenge in determining the environmental impact of SeaGen on these benthic communities was testing for significant effects against background high natural variability of the community structure caused by the high-energy environment.

Pre-installation scuba diving benthic surveys were carried out in the narrows for the initial EIA for the SeaGen project and provided baseline data. Scuba diving surveys were then carried out in March 2008 pre-installation and again in July 2008, March 2009, July 2009 and April 2010 post-installation. Four relocatable stations were established 20 m, 150 m, and 300 m southeast of the turbine installation in-line with one of the rotors and one station established 50 m to the side of the cross-arm away from the rotor blades as a control.

The data collected were transformed to the Marine Nature Conservation Review SACFOR (Superabundant, Abundant, Common, Frequent, Occasional, Rare) and SIMPER analyses were performed to determine characterizing species for each station. As expected, the species observed at all stations corresponded to very tide-swept faunal communities. The main conclusion from the results was that although minor changes were observed in species noted over the sample times, these results were driven by a combination of normal seasonal variation and the natural process of species competition and succession in a high-energy environment, and not by the installation and operation of SeaGen.

9.4.2.4
HYDRODYNAMICS

Another requirement of the EMP included evaluating the change in hydrodynamics as a result of the installed SeaGen pile structure, crossbeam, and rotors. A change in flow pattern could have a diverse range of impacts, including affecting feeding patterns of filter feeders, causing changes in sediment transport, thereby potentially increasing sediment deposition and smothering organisms, as well as safety implications for vessels. The main objective of the EMP was to obtain information about the spatial extent of the turbine wake. The downstream wake created by the device was expected to recover quickly and therefore have a minimal footprint. Comprehensive surveys using vessel-mounted ADCP were conducted and bed-mounted ADCPs were deployed. Results showed that a wake was apparent at a maximum of 300 m downstream of the turbine pile structure, but no evidence was found of the downstream wake being generated by the turbine rotors. Overall, there was no evidence of significant deviations of the ambient flow field as a result of the installation of SeaGen.

9.4.3
PRIMARY BARRIERS TO CONSENTING

The Strangford Narrows was found to be an ideal location for the installation of the SeaGen device, but since 1998 the area had been designated as a SPA, which then became a SAC under the EC Habitats Directive in 2008. The challenge for the regulators was to ensure first and foremost that the environment that had EU conservation status would not be affected by infrastructure such as a tidal turbine. This meant a comprehensive EIA had to be first carried out to produce an ES to accompany the FEPA license application. To satisfy the license, a comprehensive EMP using an adaptive management approach was carried out, and it is unlikely that the license would have been granted if EMP was not in place.

9.4.4
LESSONS LEARNED AND RECOMMENDATIONS

As mentioned previously, without an EMP and an adaptive approach, the license to install SeaGen would most likely never have been granted. Further, the extensive environmental monitoring program during the operation of SeaGen allowed for monitoring and mitigation measures to change over time and support the reduction of certain mitigation requirements. MCT recognized early in the project that the findings of the EMP would be important to a range of stakeholders, not only those interested in conservation of the Strangford Lough, but also those with wider interest in the marine energy industry. Therefore, in addition to initial public consultations, the Science Group and the wider Liaison Group were invaluable to the project; they provided guidance on monitoring and mitigation measures and contributed greatly to the success of the operation of the tidal turbine SeaGen.

9.5
BIMEP – SPAIN

According to the Basque Country's Energy Strategy, wave and wind energy are the only form of marine energy for which significant production is expected in the mid-term. The technological development and the particular geographical characteristics of the Basque Country provide suitable preconditions for the production of such energy. Furthermore, the presence and current level of development of the naval industry in the area are strong determinants for the wave energy sector to be considered a strategic and promising sector in there. In this context, the Basque Energy Board (Ente Vasco de la Energía [EVE]) together with the Instituto para la Diversificación y Ahorro de la Energía (IDAE) launched in 2008 the initiative to build the BIMEP project—a designated test site to test wave and wind harnessing devices; the platform has a maximum capacity of 20 MW.

9.5.1
LICENSING REQUIREMENTS

9.5.1.1
PRE-CONSENT REQUIREMENTS

The installation of the BIMEP is administratively complex. It involved the participation of both national and local administrations. Several ministries and departments participate in different steps of the administrative process which are as follows:

- Consult with the Spanish Ministry of the Environment, Rural and Marine Affairs (MERMA; the Spanish environmental agency) about the need to conduct an EIA (hereinafter, the environmental procedure).
- Request that the Spanish Ministry of Industry, Tourism and Trade (MITT) provide the administrative authorization for conducting the work and the Provincial Industry and Energy Dependency of the Spanish Government Delegation in Bizkaia to declare BIMEP's Public Use.
- Apply for the concession of marine-terrestrial public domain, which is a two-step process that involves a step for the Spanish Ministry of Public Works and a step for MERMA.

In 2008, the promoter (EVE) initiated the environmental procedure, which was aimed at determining the need for a full EIA. In order to make an informed decision about whether or not an EIA was needed, three documents/steps were required: 1) project submission, including the objective, description, and location of the project; 2) submission of an additional environmental appraisal document covering the actions that may cause environmental impacts, the potential environmental impacts, the mitigation and corrective measures/strategies to offset the potential negative environmental impacts, and an EMP; and 3) consultation with stakeholders carried out by MERMA. In this case, the consultation process included key stakeholders, such as fishermen and environmental NGOs.

Based on a detailed analysis of these three documents/steps, the MERMA decided that BIMEP should not be subject to a full EIA process because no significant environmental impacts would be found as a result of the project implementation. Furthermore, most of the stakeholders consulted did not envisage significant impacts on habitats, protected species, or environment. In 2011, the MITT authorized the installation of BIMEP and EVE proceeded to obtain the concession of marine-terrestrial public domain, which was granted in February 2013.

Once authorization for project execution was granted for the installation of the facilities, contracts were awarded for the supply and installation of submarine power lines and ground cables, which transfer power from the offshore sites to land. The first work started in November 2012 with horizontal drilling for the installation of the submarine power cables. Horizontal drilling allowed the landing of the submarine cables from 15 m depth to the shoreline. These cables were installed in September 2013. Finally, in July 2015 the BIMEP infrastructure facilities were officially launched and the startup for trials and final recognition certificates were received.

9.5.1.2
POST-CONSENT REQUIREMENTS

Implementation of the monitoring program proposed in the EIS of BIMEP once the exploitation and maintenance phase of the project starts.

9.5.1.3
ENVIRONMENTAL MONITORING AND KEY FINDINGS

MERMA accepted the application in June 2009 and concluded that no significant environmental impacts would be expected from implementation of the project. However, taking into account the uncertainties associated with impacts from early stage wave energy development, the ES recommended implementation of the environmental monitoring program suggested in the EIS for BIMEP project. The main environmental factors the EIS considered that could be affected by the project actions were hydrodynamics, landscape, benthic communities (Figure 9.1), fish, marine mammals, fishing activity, and archaeological and cultural resources.

The environmental monitoring program was initiated in August 2011 during the preoperational phase. During the installation of the submarine cables (Figure 9.2) in the construction phase another environmental monitoring program was also undertaken. The comparison of the results of both monitoring phases showed that the observed impacts on benthic communities, marine mammals, fish, seafloor integrity, and archaeological and cultural resources were in the range of or even below those predicted in the EIS.

9.5.2
PRIMARY BARRIERS TO CONSENTING

One of the primary barriers to consenting could be the total time needed to obtain the approval of the project. The consenting process for the BIMEP project started in July 2008 and ended in 2013 with the receipt of the concession of marine-terrestrial public domain and the authorization for project execution. In contrast, the consenting process for the Mutriku Wave Power Plant took less than two years, because it is located onshore and consequently was subject to the consenting process applicable to an "ordinary" renewable energy plant.

The varied amount of time required to obtain the final consent is attributed to whether or not an EIA is required. Until 2008, in Spain, the requirement for an EIA of wave and current technologies was decided by case-by-case analysis. Since 2013, the new EIA law makes mandatory a simplified EIA process for all energy production projects conducted in the marine environment. The new EIA law also aims to reduce the time needed to obtain the Environmental Authorization; it established a time period of no more than four months, or six months if there are justified reasons, thus significantly reducing the time needed to complete the consenting process; the process took three to 24 months under the previous law from 2008.

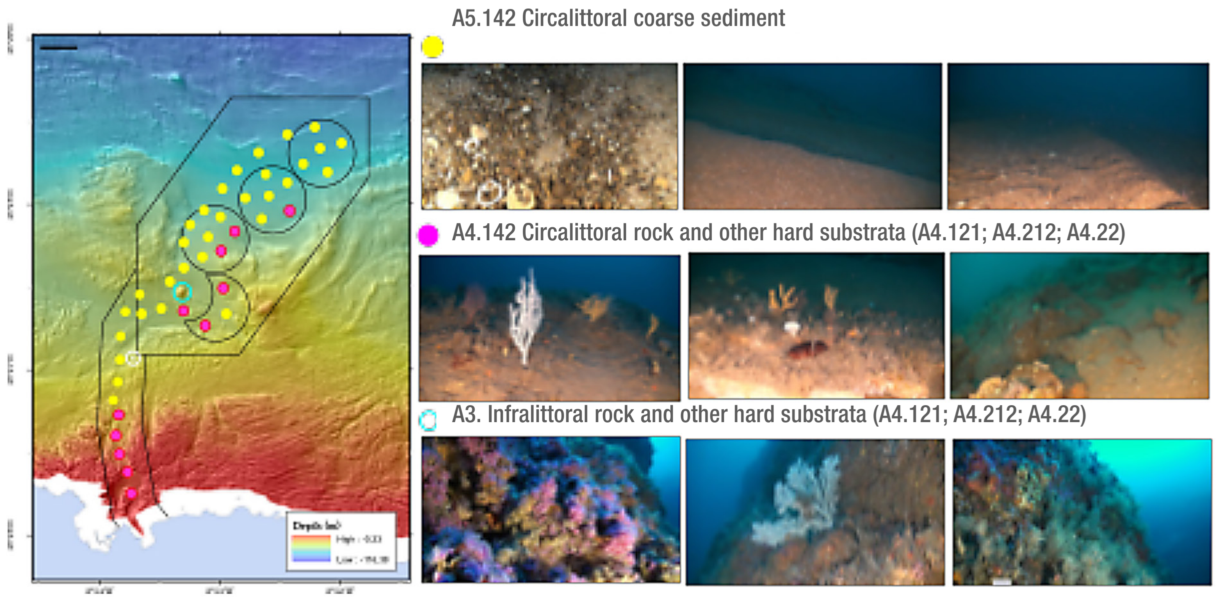


Figure 9.1. Benthic habitat classification using underwater video cameras at the BIMEP site.

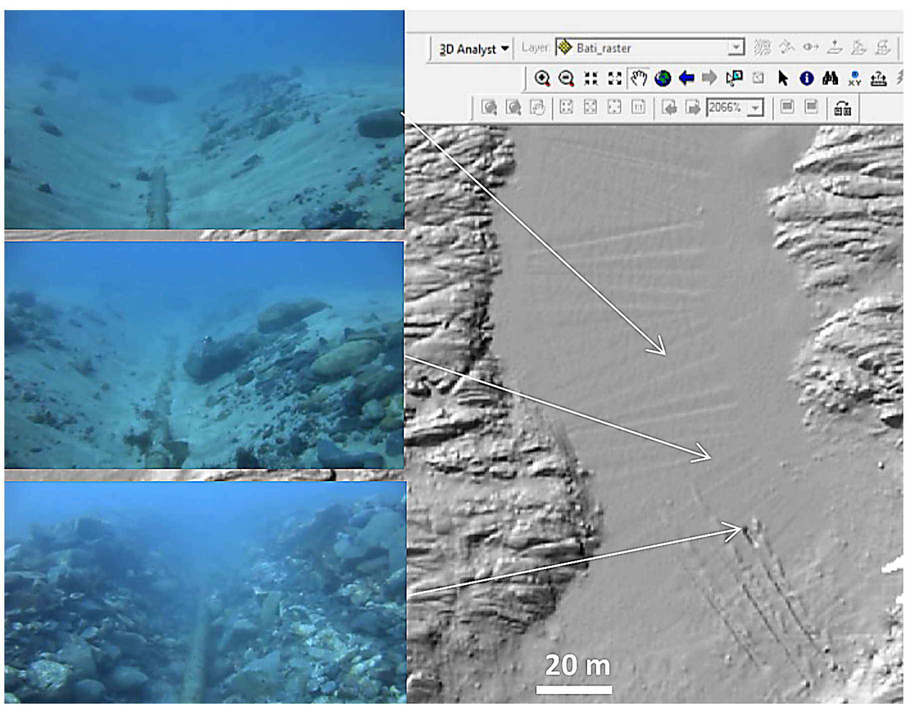


Figure 9.2. A trench approximately 60 m long by 4 6 m wide was created for each cable route at the BIMEP site.

Another issue that made the consenting process more difficult was that it was the first project of its kind. Being an innovative project means uncertainty for the nation's Administration. The Administration imposed numerous restrictions and requirements to ensure control, rather than establish a fixed number of restrictions that would allow the developer the opportunity to demonstrate that the project causes no harm. Time and experience demonstrated that the impositions were too stringent, made things more difficult for the developer, and had no benefit for the parties involved.

9.5.3 LESSONS LEARNED AND RECOMMENDATIONS

Good communication with the stakeholders in charge of the environmental permits and a sound pre-consent monitoring program and EIS were key factors in streamlining the pre-consent process. As stated above, in 2008 the EIA law established a time frame of 3–24 months for the process of obtaining the Environmental Authorization. The EIS for the BIMEP project was written in November 2008 and the Environmental Authorization was obtained in June 2009—seven months later. Saving 17 months (with respect to the worst-case scenario under 2008 EIA law) was made possible thanks to the sound EIS and pre-consent characterization of the BIMEP area and good communication with the Spanish Ministry of Environment, which has been properly informed of the findings of the EIS of BIMEP project in several meetings.

9.6 CONCLUSIONS

9.6.1 PRIMARY BARRIERS TO CONSENTING

Time-consuming and bureaucratic procedures are still indicated as the main obstacles to expeditious consenting of ocean energy projects. These obstacles are linked to the lack of knowledge pertaining to environmental interactions, and high uncertainty about some of the projects' impacts and, in some cases, to the need to consult with numerous statutory stakeholders before obtaining a final decision. Furthermore, dedicated legislation does not exist; when it does exist the administrative path and the jurisdiction over a project or marine space is not always clear. Nevertheless, regulator/administrative staff willingness to facilitate collaborative efforts has assisted developers in consulting with state agencies.

The consenting process is also considered costly, as are the environmental monitoring requirements indicated by the authorities. Monitoring requirements are higher for protected areas because of the need to ensure that conservation status would not be affected by installing ocean energy infrastructure in the marine environment. Adaptive management approaches are useful in such cases because they allow for the adaptation of monitoring planning as results show evidence of no adverse effects.

9.6.2 LESSONS LEARNED AND RECOMMENDATIONS

Consultation with statutory consultees, local stakeholder groups, and the public before and during the installation of wave and tidal energy developments is essential to overcome barriers during the consenting process. Informal consultation is important for promoting public awareness of developments, for understanding, and considering community concerns during project installation and deployment. Great value is gained from demonstrating the installation of MRE devices and acquiring knowledge from doing so. Such value may promote public understanding of the technologies and their informed acceptance of this type of project.

So far, the installation of MRE devices at sea has had no negative effects on the marine environment, but these results are based on the demonstration of single devices. Appropriate monitoring plans are thus needed to accompany the pre-commercial scale of these projects in order to be able to detect the potential impacts of upscaled installations on the marine environment. Regardless, the use of best practices during all project operations and the implementation of adaptive management approaches are essential for reducing impacts, optimizing knowledge acquisition, and reducing costs.

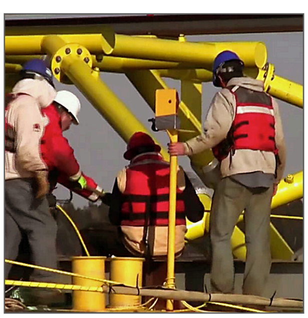
Improvement and/or adaptation of the existing legislation together with guidance on their application to the licensing of ocean energy projects are needed. In some countries these efforts have already started and are expected to evolve further in the near future.

Summary and Path Forward for Marine Renewable Energy Monitoring and Research

10.0

Chapter authors: A. Copping, I. Hutchison

This report has summarized and placed in context information about the environmental effects of MRE development, to the extent that the information is publicly available. The lessons learned, research gaps, and recommendations from each of the chapters in this report are summarized in the ensuing sections. A path forward in the face of scientific uncertainty is also discussed.



10.1 SUMMARY OF POTENTIAL INTERACTIONS ASSOCIATED WITH THE DEPLOYMENT OF MARINE RENEWABLE ENERGY DEVICES

(*Chapter 2*)

Uncertainty associated with interactions between MRE devices and marine animals and/or habitats continues to cause a high degree of risk for permitting/consenting pathways, which in turn causes uncertainty and delays in establishing the industry. By examining all of the possible interactions that might occur, a set of high-priority interactions has been identified. In most cases, interactions that most concern regulators and stakeholders are also the focus of the efforts of researchers working in this field, as well as the focus of work undertaken by developers during the consenting/permitting process. These researchers are actively seeking to understand the high-priority interactions, determining appropriate methods for recording or observing the interactions, and collaborating to develop appropriate instrumentation and data analysis methods to cost-effectively collect data during the life of MRE projects. Monitoring required of developers also focuses largely on these highly uncertain and unknown interactions.

The priority interactions have been defined using the stressor/receptor method (Boehlert and Gill 2010). Although we commonly think about the risk to marine animals from MRE devices, it is important to note that most of the perceived risk is due to uncertainty about the interactions due to the lack of definitive data. While it is possible that some real risks to marine animals and habitats from MRE devices will remain after definitive data are collected, at this point in time, the uncertainties are driving most of the perception of risk and consequent challenges to permitting/consenting commercial-scale development.

The risk to marine animals or habitats has been evaluated and illustrated in this report using a gradation of colors (orange= high risk; yellow = medium risk; green = low risk) for the operation of single devices, pilot-scale deployments, and commercial arrays. Risk is defined as the combination of the probability or likelihood of the interaction occurring; and the potential consequence or outcome severity of the interaction if it takes place. In most cases, the highest priority interactions are defined as high or medium risk, largely because of the uncertainty of the probability of occurrence; there is also uncertainty surrounding some of the potential severity of the outcomes as well.

The highest risk encounters are those associated with the collision of a marine animal with an MRE device, and the effects of underwater sound emitted from devices on the behavior and wellbeing of marine animals. There is a noted lack of definitive information for these interactions, leading to a perception of a risky endeavor for marine animals, particularly around tidal turbines.

10.2 COLLISION RISK FOR ANIMALS AROUND TIDAL TURBINES *(Chapter 3)*

Close interactions of marine animals with MRE devices, particularly tidal turbines with rotating blades, continues to rank as the highest concern for regulators and stakeholders. The perception that animals—particularly marine mammals, fish, seabirds, and sea turtles—will be killed or severely injured by blades persists despite no direct evidence that this has occurred with deployments to date. The perception of this risk is suggested from injuries to fish caused by encounters with conventional hydropower turbines. Hydropower turbines rotate at high speeds and build up pressure fields that greatly exceed those of turbines in a tidal flow; in addition, fish cannot avoid or evade turbines as they move through river systems controlled by hydropower dams. Analogues of damage to marine mammals from ship propellers are also often invoked, although ship propellers also rotate at many times the speed of tidal turbines; in addition, ships move through the water, complicating the ability of marine animals to sense and avoid them.

Researchers are focused on understanding the elements that may potentially cause a collision or other close encounter between a marine animal and an MRE device. These elements include the animal's ability to avoid the device at varying distances from the machine (avoidance); close encounters with the device in which the animal evades it at the last moment (evasion); and collisions with blades or other parts of a device (sometimes also referred to as strike). Some marine animals might also be attracted to devices; this attraction may further increase their risk of a close encounter, which may potentially result in injury. Different groups and species of animals interact with and react to MRE devices in different ways and at different scales. It is also important to consider what the consequences of a marine animal's interacting with an MRE device might be, particularly a collision. Recent research tells us that a collision does not necessarily result in death or even necessarily serious injury.

Most studies to date have focused on marine mammal and fish encounters. Fish studies have shown that small fish may move through the blade-swept area of a turbine without harm, and may gather in the turbulent wake of a turbine to feed. Marine mammals have never been observed to enter the blade-swept area of a turbine. Marine mammals are likely to sense an MRE device at a greater distance than fish, based on their sensory capabilities.

Small- to medium-sized fish are more likely to be attracted to MRE devices, potentially increasing their risk of collision. Certain species of fish naturally shoal or reef around structures in the ocean more readily than others. Seabirds may also be attracted to devices due to the presence of fish prey. Sea turtles may also be attracted but there are few data on this interaction. Marine mammals are likely to be attracted to devices out of curiosity, or perhaps due to the aggregation of certain prey fish species. Very large fish such as basking sharks may be expected to encounter risks from MRE devices that are most like those of marine mammals, due to their size and swimming patterns.

Encounters of marine animals are likely to continue to be a very active area of research in this field, and regulators are likely to require monitoring for marine mammals and possibly fish (depending on the jurisdiction) around turbines until definitive research can discount this risk, or appropriate mitigation and management measures are developed.

Current State of Understanding

With results of research studies and monitoring around only a small number of MRE devices in the water, there is currently no evidence that marine animals are likely to suffer injury or death from encounters with the devices. However, until more devices have been deployed and significant monitoring data become available, we cannot dismiss the risk from turbines (and to a lesser extent WECs) to marine animals.

10.3 RISK TO MARINE ANIMALS FROM UNDERWATER SOUND GENERATED BY MARINE RENEWABLE ENERGY DEVICES *(Chapter 4)*

Underwater sound is used by many species of marine animals for communication and navigation; so the introduction of anthropogenic sound can be disruptive to these animals. Measuring sound and sound propagation in seawater is reasonably well understood, but measuring the ambient sound in high-energy locations where MRE development is planned is complicated by noise from fast tidal and ocean currents, breaking waves, and high winds. There are reports of over 30 noise studies associated with MRE devices, including studies of ambient sound, as well as sound from the installation and operation of devices (Copping et al. 2013; Lepper 2013). However, some uncertainty remains around characterizing the sound generated by devices because of a lack of standardized measurement methods and instruments, as well as a lack of installed devices around which to gather measurements. The International Electrotechnical Commission (IEC) is developing acoustic characterization standards that will address this issue.

The distance, intensity, and frequency at which sound travels under water are affected by environmental factors including temperature, salinity, and seawater density. A small number of measurements have been made of sound emitted from a single turbine or WEC; the propagation of sound from arrays of operating MRE devices is more complex to decipher and will not be completely understood until commercial arrays are deployed. Most sound measurements from MRE devices have been gathered for single devices; although we can bound the likely acoustic outputs from the cumulative impacts of arrays, few field measurements have been made to date.

Very few studies have quantified the response of marine organisms to the construction noise of wave and tidal devices. These studies suggest that there is little reason to expect serious injury or mortality of fish or marine mammals from underwater sound generated by MRE devices. However, little direct information is available about behavioral responses. Studies of individual animal responses to noise from MRE devices are needed and the potential overall effects of noise on animal populations at risk must be considered.

Current State of Understanding

Although underwater noise is known to affect marine animals, particularly marine mammals, there is currently no clear indication whether the sound from operational MRE devices will have an effect on them. Installation operations, particularly pile driving, is likely to have short-term deleterious effects, as will the sound from vessels engaged in installation and maintenance of wave or tidal farms. However, MRE installation and vessel maintenance sounds are similar to those generated by other industries that are reasonably well understood, and for which mitigation and management measures have been established.

10.4 CHANGES IN PHYSICAL SYSTEMS: ENERGY REMOVAL AND CHANGES IN FLOW *(Chapter 5)*

Decades of reliable oceanographic measurements of tides, currents, waves, nutrient loading, and sediment are available around the world; yet these data collection efforts have rarely focused on high-energy sites where wave and tidal energy development is targeted. There are few field studies of energy removal and changes in flow caused by MRE devices, but many numerical models have been developed. Studies over recent years have begun to characterize these high-energy environments in anticipation of MRE device installations, producing data that may be input into models. A significant number of models have been created, but few are focused on environmental concerns like changes in water circulation, sediment transport, and water quality.

As reported in 2013 (Copping et al.), two detailed monitoring efforts have been carried out around tidal turbines—SeaGen (UK) and Verdant (USA). No additional studies have occurred since, although two studies in the Bay of Fundy explored the impact in tidal channels by using natural tidal variation as a proxy for MRE perturbations. Eleven modeling studies were also reported (Copping et al. 2013) that investigated energy removal associated with environmental concerns. Since that report, eight additional modeling studies have occurred. In general, there has been more focus on creating model studies to predict the impacts of tidal energy than wave energy. Tidal models are able to better predict sediment transport processes and include water quality constituents because of greater modeling complexity, greater ability to model energy removal, more reliable input data, and the use of practical numbers of turbines. Wave models are beginning to explore potential impacts on complex nearshore regions where many wave devices may be sited.

Modeling efforts and field studies indicate that nearfield changes are unlikely to be seen at tidal or wave pilot-scale projects, but field measurements are needed to validate the existing models. Other modeling and validation needs include collecting measurements of turbulence and inflow to devices, representing the diversity of device designs for tidal turbines and WECs, modeling and validating the cumulative effects of multiple devices and of MRE effects against other anthropogenic effects, and validating whether a tipping point for farfield ecosystem changes may exist, as the number of MRE devices in a waterbody increases.

Current State of Understanding

The high fidelity of hydrodynamic models presents us with the ability to understand the potential effects of energy removal and changes in flow due to MRE devices, but measurements of these effects are not likely to be available until large commercial arrays are deployed. The results of all modeling exercises to date indicate that small numbers of devices will have no measurable effect on the waters into which they are deployed.

10.5 EFFECTS OF EMF ON MARINE ANIMALS FROM ELECTRIC CABLES AND MARINE RENEWABLE ENERGY DEVICES *(Chapter 6)*

Regulatory and stakeholder concerns about the potential effects of EMFs emitted from power cables and moving parts of MRE devices appear to arise from a lack of data about the level of emissions and health concerns that have been raised about EMFs in other media (overhead electrical transmission lines, cell phones, etc.). In the oceans, we know that certain species, especially elasmobranchs (non-bony fish like sharks and skates) are sensitive to electrical currents, while others (such as salmon and sea turtles) are known to rely on magnetic fields to navigate. Experimental data indicate that some species may be attracted to EMFs, while others may try to avoid the fields. In general, animals that live in proximity to the seafloor, where export cables are likely to be located, are expected to be potentially more at risk than those living higher up in the water column. Limited field studies of EMF intensities have raised concerns that the intersection of multiple export power cables from MRE devices might create a barrier effect, preventing marine animals from reaching key feeding, mating, or rearing habitats, or even distracting long distance migrants from their journeys.

Modeling of EMF emissions from MRE devices, and analogues to other industries such as offshore wind, indicate that EMF emissions are unlikely to cause significant problems for marine animals in the early stages of MRE development. The level of uncertainty associated with the behavioral effects of marine animals in the presence of EMFs from very large conglomerations of cables may raise questions as the MRE industry advances toward deploying large commercial arrays. It should be noted that there are approximately one million electrical and communications cables laid in the world's oceans to date, according to marine mammal experts at the Arctic University of Norway (L. Morrisette, personal communication.)

Current State of Understanding

Experiments in the laboratory and measurements in the field have to date yielded little information that indicates power cables and energized portions of MRE devices are likely to pose a significant risk to marine animals or to render important marine habitats inaccessible to them. In addition, power cables in the ocean have been in place for many years for purposes of telecommunication and power transmission to remote areas. The offshore wind industry is also increasing the number of submarine cables rapidly; this issue is likely to be addressed and will be transferable to the MRE industry.

10.6 CHANGES IN HABITATS CAUSED BY MARINE RENEWABLE ENERGY DEVICES: BENTHIC HABITATS AND REEFING PATTERNS *(Chapter 7)*

Deployment and operation of MRE devices have the potential to alter habitats on the sea floor (benthic) from the footprint of the devices and anchors, and in the water column, by creating new habitats for reefing fish.

Regulatory concerns about the effects of MRE devices on benthic habitats and the organisms they support are derived largely from the presence of anchors or foundations installed on the seabed, the sweep of anchor chains or ropes across the seabed, or undesirable materials falling onto the seabed from devices installed overhead. Changes in the composition of species and food webs in a local area can be caused by the growth of benthic organisms on MRE devices. For example, mussels are prolific colonizers that can grow on portions of WECs and tidal foundations on or near the seafloor, and they may increase the level of dissolved nutrients and support other organisms that act as prey for larger species. This colonization may act in conjunction with biofouling on MRE devices, creating even higher levels of nutrients and low oxygen conditions.

Evaluation of the potential effects on the benthic environment is hampered by the lack of detailed seasonal data on benthic organisms living in and on the bottom sediments, and the very large naturally occurring variability of these communities in all parts of the ocean. In a few areas where very detailed benthic surveys have been carried out over periods of years, potential changes that might be linked to the installation and operation of MREs are unlikely to be measurable over this background natural variability.

The presence of MREs in the water column as well as near the seafloor will attract marine organisms, particularly reefing fish. The terms reefing and FAD are both used to describe this phenomenon of changing marine animal behavior to concentrate organisms in the vicinity of structures in the sea. However, neither reefing nor MRE effects on benthic organisms are unusual or peculiar to the MRE industry. All structures in the sea have the potential to change bottom habitats and attract animals, including natural structures like reefs, boulders, cliffs, and outcroppings, as well as those placed there by humans.

Current State of Understanding

There has been no evidence of widespread or long-term changes in benthic habitats will occur except in the immediate vicinity of WECs and tidal turbines. The inherent wide variability of species and organisms that make up benthic communities makes it extremely difficult to measure changes due to the installation or operation of a small number of MRE devices. Particular groups of fish are known to reef around structures in the water column. The addition of MRE devices is not likely to present a risk to the reefing fish and may in fact provide additional shelter or foraging opportunities for them.

10.7 MARINE SPATIAL PLANNING AND MARINE RENEWABLE ENERGY *(Chapter 8)*

Marine spatial planning is under way in many coastal nations, and several are explicitly using the processes to enable MRE development. Eleven countries actively involved in MRE development were surveyed for this comparison; the results indicate that the countries are at varying stages of implementing MSP. Four countries reported having a formal MSP process, four countries use a coastal management planning process that can include elements similar to those associated with MSP, and three countries reported not using MSP. As a developing sector, MRE has yet to be fully integrated into the various marine-based planning systems such as MSP. Although many countries are not formally incorporating MSP into their development and regulatory processes, certain MSP elements are being incorporated into existing marine development frameworks.

Survey respondents indicated that the various national planning systems that are in place offer enough flexibility to incorporate MRE development activities. Data gaps on potential environmental effects of MRE development have in some cases spurred research programs to systematically address these gaps in an effort to better implement MSP. Some countries reported addressing cumulative impacts of MRE and other development through existing policies and procedures, while other countries report not having a systematic process in place. Interaction with stakeholders is also a tenet of MSP; most countries reported that conflicts are dealt with on a case-by-case basis rather than through a systematic procedure. The primary factors limiting implementation of MSP for MRE planning include lack of pertinent data and resources to implement the programs; political will was also a constraint cited by several countries. Overall, the path forward for implementing marine spatial planning to support MRE development points to the need to reduce uncertainty in environmental effects.

Current State of Understanding

MSP has the potential to be an important tool in establishing the MRE industry among existing and future valuable uses of the marine environment, for most coastal nations. While many of the nations surveyed are involved in some form of MSP, there is great variability and room for many countries to improve their assessment of coastal uses and to apply principles of MSP to aid the MRE industry.

10.8 CASE STUDIES THAT EXAMINE SITING AND PERMITTING/CONSENTING OF MARINE RENEWABLE ENERGY DEVICES *(Chapter 9)*

Case studies have been presented as examples of consenting processes that have been carried out to meet regulatory requirements in Europe and North America — two tidal projects, one wave project and one wave test center. Lessons learned from these case studies assist in providing insight into facilitating future deployments of MRE devices.

10.9 PRIORITY INTERACTIONS

As single device deployments continue and development of the first commercial arrays is on the horizon, several critical interactions between MRE devices and marine animals continue to concern regulators and stakeholders.

The potential for collisions between a marine mammal, fish, or seabird and a rotating tidal turbine blade remains the interaction of greatest concern that slows and complicates siting and permitting of devices. Driving this concern is largely the uncertainty of whether collisions are likely to take place, and if such a rare event were to occur, could it be observed? The need for new and innovative instruments and observational techniques is likely to remain a top priority for researchers, developers, and the regulatory community for several years to come.

Underwater sound generated by wave and tidal devices continues to be of concern to the overall MRE community. This concern is driven by a combination of uncertainty about the amplitude and frequencies emitted and propagated from MRE devices, and the knowledge that underwater sound is an important medium for communication, navigation, and feeding strategies among marine mammals, fish, and other marine organisms. The need to accurately measure ambient noise fields in areas where MRE devices are slated for deployment, coupled with the challenges of accurately measuring noise emitted from a single MRE device, complexities of sound propagation from multiple devices, challenges of observing marine animal behavior, and the complex cause-and-effect relationship between the sound source and the animal, are likely to continue to make underwater sound a priority for investigation and possible mitigation into the future.

Concerns raised about the effects of EMFs on marine animal behavior, development, and habitat use continue to affect siting and permitting processes, based on the lack of certainty around exposure, dosage, and effects on animals in proximity to export power cables and energized portions of MRE devices. While active research in this area is ongoing and beginning to yield answers, regulators will probably continue to raise the issue with each new consenting application.

10.10 RETIRING RISK

Research studies and monitoring results from deployments of single devices (or small groups of devices) have provided information about risks associated with several key interactions between MRE devices and marine animals/habitats. However, the risks associated with many interactions continue to be driven by uncertainty, and we continue to have limited insight into how those risks will scale as we move toward larger deployments over longer time scales. In order to move forward with a viable industry, these risks need to be understood and managed in ways that are similar to how they are managed in other established offshore industries. Those interactions that are not causing harm to the marine environment need to be "retired," and the focus of research and monitoring studies needs to be directed toward higher priority interactions. Eventually all interactions should be retired, or mitigated through a range of actions including avoidance and minimization.

Perceived risks to the marine environment from MRE devices can be examined based on the level of uncertainty associated with the specific interaction of concern. These perceived risks can be classified into three categories (as illustrated in Figure 10.1):

- low-risk interactions that have been discounted or retired from ongoing monitoring (green); these risks could also include those that are well understood but might potentially be significant.
- interactions that have a high level of uncertainty associated with the risk they may pose to the marine environment, and require further monitoring and perhaps an adaptive management approach prior to scaling up to arrays to determine this level of risk (yellow); and
- interactions that are known to be related to high levels of risk to the marine environment, and that will require mitigation through improved siting, improved design or operation of the devices, and perhaps an adaptive management approach, prior to scaling up to arrays. A key example is the underwater noise from pin piling for installation of tidal or wave devices. In certain jurisdictions that require mitigation, standard environmental mitigation and management measures can be used to mitigate the effects (orange).

Many of the perceived risks for MRE development currently fall in the largest piece of the pie (yellow) and represent the bulk of the monitoring requirements that wave and tidal developers face in order to obtain permission to deploy and operate projects. If evidence can be gathered through targeted strategic research studies to identify and eliminate or adequately reduce the uncertainties that fall in the largest piece of the pie, fewer monitoring requirements would be placed on wave and tidal projects, thereby expediting the overall environmental permitting process. This would then move many of the uncertain risks from the large yellow category to the retired risk category (green), or identify risks that require mitigation (orange), as shown in Figure 10.1. The scope of this undertaking will require a coordinated, strategic research investment by governments, as well as cooperation and collaboration among researchers, regulators, and MRE developers.

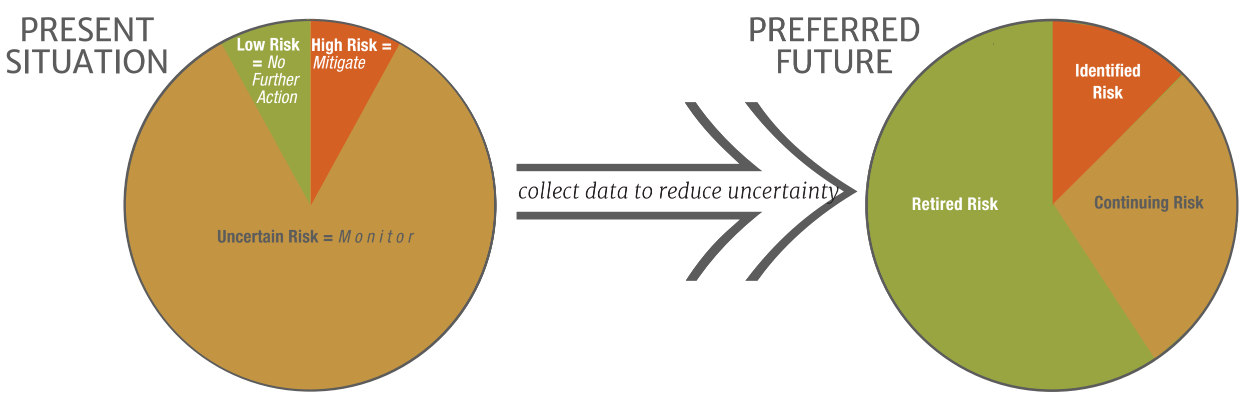


Figure 10.1 Categories of risk and uncertainty reduction pathways. The risk categories can be considered as low or discountable risk (green); medium risk (yellow); and identified risks (orange) for which mitigation strategies are needed. Moving from the present situation (left) to the preferred future condition (right), through increased data collection, will help accelerate the MRE industry. (Figure courtesy of Brian Polagye and Andrea Copping)

10.11
A CONSTRUCT FOR MOVING FORWARD IN THE FACE OF UNCERTAINTY

Maintaining the momentum of MRE deployments, and further accelerating the pace of development, requires that the scientific research, regulatory, and development communities come together to address the priority interactions that are likely to continue to arise as regulatory (consenting) concerns. MRE device and project developers need to be part of the conversation to ensure that solutions that will satisfy regulators are feasible and reasonable within the context of developing early stage and commercial MRE projects.

A path forward that could decrease uncertainty for priority interactions, while maintaining momentum with early deployments, pilot projects, and commercial arrays requires the following elements:

- identification of interactions that can be routinely monitored for some period after deployment; and
- development of a set of options and tools that can be followed to gather data required by regulators that are consistent with scientific findings to date, and that can be accommodated within the time frames, spatial considerations, and costs constraints of MRE projects. With more experience, the options and tools can be honed, eventually becoming a set of good practices for collection of interaction data around MRE devices.

10.12
MONITORING PRIORITY INTERACTIONS

As the industry moves forward, the goals must be to reduce uncertainty that will lead to retirement of many risks; to better understand those interactions that will continue to require ongoing monitoring; and to create mitigation strategies for interactions considered to cause harm. We must understand which interactions fall into each category. Interactions among marine animals/habitats and MRE devices that are deemed important by the regulatory community can be approached through three strategies (examples that fit each of these strategies can be found in Table 10.1):

- Certain interactions can be effectively monitored now with existing instruments, platforms, and technologies. However, significant research challenges may remain in the design and installation of the instruments, as well as in the acquisition, analysis, and interpretation of data streams.
- Other interactions would benefit from the input of targeted strategic research efforts in the near term. These inputs could help to decrease the costs and perhaps the number of years that monitoring would be required over the life of the wave or tidal project.
- The only viable path forward at this time is invest in upfront strategic research studies as there are no feasible monitoring methods available.

10.13
DEVELOPING GOOD PRACTICES

The goal of data collection around early MRE devices and arrays is to decrease the uncertainty around each priority interaction, to inform the design of monitoring and mitigation programs that are commensurate with the real risks posed by the devices, as well as to protect the marine animals and habitats nearby. As we better understand the potential outcomes of encounters of animals with turbines, animal reactions to noise from WECs and turbines, potential barrier effects due to EMF from power cables, and all the other possible deleterious outcomes, the community of researchers, regulators, developers, and others can develop effective monitoring practices where they are warranted, and inform mitigation strategies if ongoing risks are identified. Once effective monitoring and mitigation actions are applied by early MRE project developers, experience with these programs will allow us to define good practices that can be applied to upcoming MRE projects, thereby accelerating the siting and permitting from single devices to commercial-scale arrays.

10.13.1
REGULATORY DRIVERS FOR MONITORING

The type, quantity, duration, and quality of data collected for baseline assessments and post-installation monitoring will be determined by the regulatory authorities in each jurisdiction pursuing MRE development. Post-installation data must be compared with baseline conditions collected before WEC or turbine deployment, in order to understand the potential

Table 10.1. Examples of interactions between marine animals and MRE devices that can be addressed through monitoring and strategic research investments. There are other interactions that fall into each category as well that are not highlighted here.

Strategy for Measuring Interaction	Interaction	Key Methods and/or Instruments Currently Available or Needed
Interactions that can be monitored now	Harbor porpoise interaction with tidal devices, observations of evasion (within one to two diameters of the device) and/or avoidance (at greater distances from the device).	CPODs and floating hydrophones are mostly available now, although more research is needed on integration of instruments and data streams.
	Large whales changing movement patterns around wave and tidal arrays.	Boat-based and aerial observations. Passive acoustic arrays to detect, localize, and characterize species. Additional research could benefit passive acoustic monitoring location and characterization.
	Seals changing movement patterns around tidal arrays	Boat-based and aerial observations. Active tags on seals. Additional research on use and cost-effectiveness of tags could provide benefit.
	Monitoring interactions of fish around tidal turbines, including evasion and passage through the turbine.	Acoustic cameras and multibeam instruments placed on both sides of the turbine. Additional algorithm development could improve species recognition.
Strategies for measuring interactions that would benefit from research investment upfront	Interactions of marine animals, notably marine mammals and large fish, with tidal turbine blades.	Instruments that can observe interactions of animals around tidal turbines are being considered, but no such instrument exists that can monitor accurately at a reasonable cost of time and effort. The likely rare occurrence of these events makes it significantly more difficult to measure.
	Marine mammals and other animals evading/avoiding specific parts of a tidal or wave device, such as the surface expression, rotors, etc.	Instruments, such as optical cameras and acoustic cameras, and integrated packages of acoustics and optics, needed to examine close interactions. Research needed to improve integration of instruments and algorithms for data analysis, and the development of cooperative targets for calibration of instruments.
Strategies for measuring interactions where targeted research is essential for moving forward	The population implications of individual marine mammals, seabirds, sea turtles, and large fish avoiding tidal or wave arrays.	Targeted studies to improve baseline assessment of populations including distributions, population structure, feeding and migrating behavior.
	Large marine mammal interactions and potential for entrapment in mooring lines from WECs and floating tidal arrays.	Modeling studies supported by assessments of marine mammal interactions with mooring lines on surrogate devices (for example floating oil rigs, radar installations).

impacts the devices. This before and after comparison requires that baseline data be collected with the rigor and specific techniques that allow for future comparisons. At the same time, it is vital that baseline assessment and monitoring data be focused on the likely risks from MRE devices; extensive baseline data collection not closely related to potential effects places an unsustainable burden on MRE developers, particularly at the start of this fledgling industry. The collection of extensive before and after monitoring data does not ensure that differences will be noted; studies that look at rates of change and gradients in population and habitat size can help to elucidate trends, even when absolute changes cannot be documented.

As an illustration of the type and duration of monitoring requirements that MRE developers face, the first two columns of Table 10.2 and Table 10.3 indicate (generally) the assessment and monitoring requirements as they stand now, for the tidal and wave sectors, respectively. These requirements are based on those drawn from consenting applications in the UK, unless otherwise noted. Consent applications to date have focused on single devices, and the very start of commercial arrays (like MeyGen), as reflected in these tables.

10.13.2
STRATEGIC RESEARCH STUDIES

Development of monitoring practices requires a coordinated approach to conducting research with input from regulators, stakeholders, industry, and the research community, with the purpose of determining where gaps might exist in understanding fundamental processes that drive interactions between the marine environment and MRE devices, as well as determining where gaps exist in the instrumentation and techniques necessary for data collection and analysis. Filling these gaps through strategic research studies is a necessary step for determining whether there are risks from MRE devices that require ongoing monitoring and perhaps mitigation, or could be retired, as well as determining the most effective way to create ongoing data collection programs. Tables 10.2 and Table 10.3 consolidate: examples of the information that is needed; strategic research investments that could expedite the development of monitoring protocols and/or decrease the need for extensive monitoring; the approximate scale of the cost of those investments; and lessons learned from strategic research.

Designing strategic research studies will hasten understanding of priority interactions and allow for the development of effective monitoring plans. These studies need to be scoped to include an estimate of the costs of the studies, as well as an assessment of the value each study will bring to moving the development of good practices for monitoring and mitigation forward.

As MRE development progresses in multiple countries, it will benefit the industry to have researchers from around the world collaborate in the development of strategic research priorities, planning strategic research studies, and carrying out joint planning and implementation of studies. A working example of this collaborative approach to strategic research planning is the UK's Offshore Renewables Joint Industry Programme for Ocean Energy (ORJIP), which brings together regulators, agencies, stakeholders, industry, and researchers to ensure that key consenting issues and risks are addressed in a coordinated manner (ORJIP 2015). At these early stages of the industry, sharing of available information (for example through *Tethys: http://tethys.pnnl.gov*) and cross-boundary cooperation on studies ensures that each advance in priority interactions is understood broadly, and learning progresses exponentially.

Table 10.2. Tidal energy project-level monitoring requirements, gaps in information and capabilities for monitoring around tidal installations, strategic research investments to address those gaps, and lessons learned from those research investments.

Note: The United States, Canada, and many other nations have not standardized or formalized baseline assessment (pre-installation) requirements for tidal energy, nor have they developed specific monitoring requirements for construction and operation. The requirements listed in this table are based on those from the UK and/or other European nations, unless otherwise noted. The requirements listed here are gleaned from consent applications to date for single devices and small arrays. The cost drivers are based on funds spent to date by developers. The approximate scale of costs for monitoring and research investments is derived from United States projects.

Key Interaction	Current Assessment and Monitoring Requirements	Gaps in Available Information, Instrumentation, and Analysis Capabilities	Strategic Research with Approximate Scale of Costs	Lessons Learned/Impacts and Effects on Key Cost Drivers
Collision/evasion for marine mammals, fish, seabirds, and sea turtles (See details in Chapter 3.)	Baseline survey requirements determined on a case-by-case basis in most jurisdictions; underpinned by Survey, Deploy, Monitor strategy in Scotland. During operation, monitoring is required to investigate behavior/activity around device, to detect animals within a specified distance to the turbine for collision, and to facilitate mitigation measures.	Data collected by acoustic/optical instruments, associated platforms; data management and analysis need further development. Need to better understand spatial and temporal patterns of interactions. Acoustic/optical observations are needed at different scales than collision, largely for fish.	Intensive monitoring around first arrays to understand how animals interact with single devices and arrays. (Moderate to high costs). Further research on marine mammal/fish behavior around single operating devices and arrays to quantify avoidance rates for input in collision risk modeling (CRM). Need to build evidence base to assess whether collision is likely to be an issue. Data on avoidance and behavior need to be collated and organized so that data collected can feed into the development of CRMs. (Moderate to high costs). Better instrumentation and methodologies are needed to improve efficiencies of monitoring. (Moderate to high costs).	Understanding the scale and potential for interactions results in costs savings in developing appropriate monitoring methodologies. Significant cost efficiencies from research into better instruments and technologies. Efficacy of data improved; produced better quality data for lower cost. Key cost drivers are baseline assessment and need for ongoing monitoring during operation.
Attraction (See details in Chapter 3 – Collision, and Chapter 7 – Changes in Habitats.)	Baseline surveys not required in UK, but may be in other jurisdictions. US and Canadian regulators requesting monitoring for fish interactions.	None at this time	Improved methodologies for collecting baseline data are needed, that can be applied to operational monitoring also. (Moderate cost). The development and operation of persistent swarms of instruments may assist with collecting improved data; however, power use and costs must be greatly improved to make these clusters viable.	Monitoring cost efficiencies could result from research into better instruments and technologies. Efficacy of data could be improved, and could produce better quality data for lower cost.
Avoidance (See details in Chapter 3 – Collision.)	No requirements at this time		Improved modeling approaches are needed to determine whether significant risk exists, and to design monitoring programs, if needed. (Low cost)	Key cost drivers are baseline assessment, if required, and potential for monitoring required during operation. May retire risk OR May require long-term observation program. Need research for improved observation methodologies

Table 10.2 continues next page

Table 10.2 continued

Key Interaction	Current Assessment and Monitoring Requirements	Gaps in Available Information, Instrumentation, and Analysis Capabilities	Strategic Research with Approximate Scale of Costs	Lessons Learned/Impacts and Effects on Key Cost Drivers
Mooring Line Interactions (See Chapter 3 – Collision.)	No requirements at this time	None at this time	Research is needed to determine whether significant risk exists, and to design monitoring program, if needed. (Low cost)	May retire risk OR May require long-term observation program. Need research for improved observation methodologies
Effects of underwater noise and vibration on marine mammals (See Chapter 4 – Noise.)	Baseline assessment required in some instances to inform Marine Mammal Protection Plans where "noisy works" are planned, monitoring during construction only for "noisy works" (JNCC 2010). Usually involves the establishment of "observation and mitigation zones." Marine mammal observer support often required.	Acoustic signatures needed from most single turbine designs and arrays. Lack of understanding of effects on marine mammals and some fish from acoustic output of devices.	Develop acoustic signatures of devices to build evidence base of operational noise levels. Need to standardize measurement of operational acoustic data so they are comparable across projects. (Moderate cost). Behavioral observations of marine mammals and fish around turbines, in conjunction with measurement of acoustic output amplitude and frequency. (Moderate to high cost).	Research investigations could reduce or eliminate the need for baseline acoustic surveys and acoustic monitoring during operation.
Seabed impacts from the installation and presence of support structures (see Chapter 7 – Changes in Habitats)	No baseline assessment requirements at this time, although developers typically survey seabed prior to development. Periodic monitoring at test sites to better understand potential impacts (such as undertaken at EMEC, BIMEP)	None	Development of tools to decrease cost of benthic sample collection and organism identification that is specific to MRE. (Low cost)	Potential to reduce or eliminate need for benthic sampling in conjunction with seabed surveys
Effects of EMFs on migratory fish and elasmobranchs (See Chapter 6 – EMF.)	None at this time, although US regulators have required baseline surveys for ambient EMF and monitoring after installation.	Need to understand linkages between EMF strength and behavior changes in marine animals.	Laboratory and field studies to determine what strength and frequency of EMFs may cause deleterious alterations in behavior for benthic organisms and fish. (Moderate to high cost).	Potential to retire risk.

Table 10.3. Wave energy project-level monitoring requirements, gaps in information and capabilities for monitoring around WEC installations, strategic research investments to address those gaps, and lessons learned from those research investments.

Note: The United States, Canada, and many other nations have not standardized or formalized baseline assessment (pre-installation) requirements for tidal energy, nor have they developed specific monitoring requirements for construction and operation. The requirements listed in this table are based on those from the UK and/or other European nations, unless otherwise noted. The requirements listed here are gleaned from consent applications to date for single devices and small arrays. The cost drivers are based on funds spent to date by developers. The approximate scale of costs for monitoring and research investments are derived from United States projects.

Key Interaction	Current Assessment and Monitoring Requirements	Gaps in Available Information, Instrumentation, and Analysis Capabilities	Strategic Research with Approximate Scale of Costs	Lessons Learned/Impacts and Effects on Key Cost Drivers
Collision/evasion for marine mammals, fish, seabirds, and sea turtles (See details in Chapter 3.)	No requirements.	Lower risk concerns than for tidal, but need to understand spatial and temporal patterns of interactions of marine mammals, seabirds, and fish. Data collected by acoustic/optical instruments, associated platforms; data management and analysis need further development.	Better instrumentation and methodologies are needed to improve efficiencies of monitoring. (Moderate to high costs).	Cost efficiencies could result from research into better instruments and technologies, and efficacy of data could be improved, and would produce better quality data for lower cost. Key cost drivers are baseline assessment, if needed, and monitoring during operation.
Attraction (See details in Chapter 3 – Collision, and Chapter 7 – Changes} in Habitats.)	Baseline surveys not required in UK, but may be in other jurisdictions. US and Canadian regulators requesting monitoring for fish interactions.	Acoustic/optical observations are needed at different scales than collision, largely for fish.	Improved methodologies for collecting baseline data are needed, that can be applied to operational monitoring also. (Moderate cost).	Monitoring cost efficiencies could result from research into better instruments and technologies. Efficacy of data could be improved, and could produce better quality data for lower cost. Key cost drivers are baseline assessment, if required, and potential for monitoring required during operation.
Avoidance (See details in Chapter 3 – Collision.)	Baseline surveys not required in UK, but may be in other jurisdictions. US and Canadian regulators are requesting monitoring for fish interactions.	None at this time	The development and operation of persistent swarms of instruments may assist with collecting improved data; however, power use and costs must be greatly improved to make these clusters viable. Improved modeling approaches are needed to determine whether significant risk exists, and to design monitoring programs, if needed. (Low cost)	May retire risk OR May require long-term observation program. Need research for improved observation methodologies

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Table 10.3 continued

Key Interaction	Current Assessment and Monitoring Requirements	Gaps in Available Information, Instrumentation, and Analysis Capabilities	Strategic Research with Approximate Scale of Costs	Lessons Learned/Impacts and Effects on Key Cost Drivers
Mooring Line Interactions (See Chapter 3 – Collision.)	No requirements at this time, but issue has been raised in US by regulators.	Little information available, but lots of conjecture.	Research needed to determine whether significant risk exists, and to design monitoring program, if needed. (Low cost).	May retire risk OR May require long-term observation program. Need research for improved observation methodologies
Effects of underwater noise and vibration on marine mammals (See Chapter 4 – Noise.)	Baseline assessment required in some instances to inform Marine Mammal Protection Plans where "noisy works" are planned, monitoring during construction only for "noisy works" (JNCC 2010). Usually involves the establishment of "observation and mitigation zones." Marine mammal observer support often required.	Acoustic signatures are needed from most single WEC designs and arrays. Lack of understanding of effects on marine mammals and some fish from acoustic output of devices.	Develop acoustic signatures of devices to build evidence base of operational noise levels. Need to standardize measurement of operational acoustic data so they are comparable across projects. (Moderate cost). Behavioral observations of marine mammals and fish around WECs, in conjunction with measurement of acoustic output amplitude and frequency. (Moderate to high cost).	Research investigations could reduce or eliminate the need for baseline acoustic surveys and acoustic monitoring during operation.
Seabed impacts from the installation and presence of support structures (see Chapter 7 – Changes in Habitats)	No baseline assessment requirements at this time, although developers typically survey seabed prior to development. Periodic monitoring at test sites to better understand potential impacts (such as undertaken at EMEC, BIMEP)	None	Development of tools to decrease cost of benthic sample collection and organism identification that is specific to MRE. (Low cost)	Potential to reduce or eliminate need for benthic sampling in conjunction with seabed surveys
Effects of EMFs on migratory fish and elasmo-branchs (See Chapter 6 – EMF.)	None at this time, although US regulators have required baseline surveys for ambient EMFs and monitoring after installation.	Need to understand linkages between EMF strength and behavior changes in marine animals.	Laboratory and field studies to determine what strength and frequency of EMFs may cause deleterious alterations in behavior for benthic organisms and fish. (Moderate to high cost).	Potential to retire risk.

10.14 NEXT STEPS

The information gathered in this report and reflected in Table 10.2 and Table 10.3 should be considered as a starting point from which a process developing good practices can proceed. A concerted effort is needed to bring together researchers to further develop the content of required strategic research studies that will inform the priority interactions. The research community has the responsibility to ensure that strategic research studies are scientifically valid and feasible, as well as being designed to decrease the uncertainty that continues to slow and challenge siting and consenting/permitting processes for wave and tidal energy development. Any strategic research undertaken must be vetted with the regulatory community to ensure that the outcomes address pertinent regulatory requirements. Similarly, MRE device and project developers must engage to ensure they understand what is needed to facilitate permitting/consenting; the industry must also weigh in with practical considerations of what is feasible within the constraints of project timelines and budgets.

Ultimately, through the contribution of strategic research studies, in cooperation with regulators and developers, a set of good practices could be developed. These practices are likely to take the form of the following:

- a standardized set of data collection needs;
- a framework that would be adaptable to meet differing regulatory needs and legislative requirements in different nations and regions;
- mechanisms for funding research across international boundaries to ensure that the most efficient studies are carried out in the most appropriate locations, with the complement of experienced researchers;
- a clear indication of additional strategic research needed to provide monitoring guidance and/or elucidate interactions sufficiently to reduce monitoring requirements;
- reasonable costs estimates for routine monitoring; and
- methods and pathways for further efficiencies and cost reductions in the future.

10.15 REFERENCES

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FOR MORE INFORMATION

Annex IV State of the Science full report and executive summary available at: *http://tethys.pnnl.gov/publications/state-of-the-science-2016*

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Go to *http://tethys.pnnl.gov* for a robust collection of papers, reports, archived presentations, and other media about MRE development.